STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

BULLETIN NO. 63

SEA-WATER INTRUSION IN CALIFORNIA

GOODWIN J. KNIGHT
Governor

HARVEY O. BANKS
Director of Water Resources

November, 1958

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GOODWIN J. KNIGHT
GOVERNOR

HARVEY O. BANKS
DIRECTOR

ADDRESS REPLY TO
P. O. BOX 388 SACRAMENTO 2
1120 N STREET HICKORY 5-4711

STATE OF CALIFORNIA

Department of Water Resources

SACRAMENTO

November 10, 1958

HONORABLE GOODWIN J. KNIGHT, *Governor,*
and Members of the Legislature of
the State of California

Water Pollution Control Boards

GENTLEMEN:

I have the honor to transmit herewith Bulletin No. 63 of the State Department of Water Resources, entitled "Sea-Water Intrusion in California," authorized by Chapter 1500, Statutes of 1951, and by Section 229 of the Water Code. Chapter 1500 directed that an investigation be made to develop design criteria for the correction or prevention of damage to underground waters of the State by sea-water intrusion. Extensive field and laboratory experimental activities were undertaken as a part of this investigation.

Intrusion of sea water, resulting from severe overdraft, has already damaged some of the State's most important ground water basins. Unless effective measures to correct this condition in these basins and to prevent intrusion into other coastal basins are commenced immediately, extensive and irreparable damage will inevitably result.

As part of the investigation for this report, a large-scale field experimental project was constructed and operated at Manhattan Beach, Los Angeles County, by the Los Angeles County Flood Control District, under a cooperative contract. The object of this project was to determine the feasibility of correcting and preventing sea-water intrusion by creating a pressure ridge by injecting fresh water into the affected aquifers through wells. The University of California, both at Berkeley and Los Angeles, and the United States Geological Survey, under contract, conducted extensive laboratory studies of various aspects of the overall problem. The Department of Water Resources studied all known coastal ground water basins to determine the extent of the problem and develop plans for correction.

This bulletin discusses the present status of sea-water intrusion into coastal ground water basins in California, describes methods of control, summarizes prior and current experimental studies applicable to the determination of design criteria for the prevention or control of sea-water intrusion, and presents preliminary plans for prevention and control of sea-water intrusion into ground water basins.

Very truly yours,

Harvey O. Banks

HARVEY O. BANKS
Director

ACKNOWLEDGMENT

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United States Department of the Navy
University of California at Berkeley, Richmond Sanitary Engineering Research Field Station
University of California at Los Angeles, Department of Engineering

The Department gratefully acknowledges their help and cooperation, in toto.

ORGANIZATION

STATE DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

HARVEY O. BANKS	Director of Water Resources
M. J. SHELTON	Deputy Director of Water Resources
WILLIAM L. BERRY	Chief, Division of Resources Planning
CARL B. MEYER	Principal Hydraulic Engineer Chief, Special Activities Branch

The water quality activity under which this report was prepared is directed by

MEYER KRAMSKY *	Principal Hydraulic Engineer

assisted by

WILLARD R. SLATER	Supervising Hydraulic Engineer

In the Southern California District this investigation was conducted under the direction of

MAX BOOKMAN	District Engineer

assisted by

DAVID B. WILLETS	Supervising Hydraulic Engineer

The report was prepared by

LAURENCE B. JAMES	Chief Geologist
RAYMOND C. RICHTER	Supervising Engineering Geologist
JACK J. COE	Senior Hydraulic Engineer
ROBERT G. THOMAS	Senior Engineering Geologist
E. PHILLIP WARREN	Associate Statistician
RUSSELL R. KLETZING	Associate Attorney

assisted by

PHILIP J. LORENS	Senior Engineering Geologist
COLE R. McCLURE	Senior Engineering Geologist
ALAN L. O'NEILL	Senior Engineering Geologist
ROBERT C. FOX	Associate Engineering Geologist
WALTER L. TERRY	Associate Hydraulic Engineer
JACK H. WYATT	Associate Public Health Chemist
ROBERT FORD	Assistant Engineering Geologist
DONALD McCANN	Assistant Engineering Geologist
DAVID LEVE	Assistant Hydraulic Engineer
TOM NAGEL	Junior Engineering Aid

P. A. TOWNER, Chief Counsel

PAUL L. BARNES, Chief, Division of Administration

ISABEL C. NESSLER, Coordinator of Reports

* Prior to March 18, 1957, P. J. Coffey was in charge of this activity and prior to June 30, 1956, Carl B Meyer was in charge.

CALIFORNIA WATER COMMISSION

ORGANIZATIONAL CHANGES

On July 5, 1956, pursuant to the provisions of Chapter 52, Statutes of 1956, First Extra Session, the Department of Water Resources was created and placed under the control of a director appointed by the Governor. The department succeeded to, and is vested with, all the powers, duties, purposes, responsibilities, and jurisdiction vested in the former Division of Water Resources and the State Engineer, with the exception of certain powers pertaining to water rights which were vested in the State Water Rights Board.

CHAPTER I

INTRODUCTION

Prior to 1900, utilization of ground water supplies was relatively limited in California. However, rapid development in the use of ground water since the turn of the century has created many serious problems, including overdraft and sea-water intrusion. Sea-water intrusion was first noted in California about 1906 along the bayward margin of Mission Valley in San Diego County. Since 1940, long continued ground water draft, a protracted period of dry years, and increasing agricultural, municipal and industrial demands have lowered ground water elevations below sea level along the seaward margins of many ground water basins. In many instances the natural seaward hydraulic gradient has been reversed. Thus, as a result of this ground water overdevelopment, extensive damage caused by sea-water intrusion has already occurred in numerous ground water basins adjacent to the coast and saline inland bays of California, with resultant large economic losses. Unless means of prevention and control of this source of degradation are undertaken now, further and more widespread deterioration of ground water supplies will occur in the areas already affected; and a large number of other ground water basins, in which geologic and hydrologic conditions are conducive to sea-water intrusion, will also suffer from this source of degradation.

AUTHORIZATION FOR INVESTIGATION

The California State Legislature, by Chapter 1500, Statutes of 1951, appropriated $750,000 to the State Water Resources Board for an experimental program to determine criteria for the prevention and control of sea-water intrusion into ground water basins bordering the California coast and inland bays. The legislation is quoted as follows:

> "The sum of seven hundred fifty thousand dollars ($750,000) is hereby appropriated out of any money not otherwise appropriated in the Postwar Unemployment and Construction Fund, or, in the event that such amount of money is not available therefrom then to the extent not so available out of any money not otherwise appropriated in the General Fund to the State Water Resources Board for investigational work and design criteria for correction or prevention of damage to underground waters of the State by sea-water intrusion in the West Coast Basin of Los Angeles County and other critical areas. The cost of such investigation and study shall include the cost of providing water, water injection wells, observations wells, water spreading grounds, pipe lines, equipment, rights of way, and other facilities necessary to introduce water into the water-bearing aquifers. The board is authorized to cooperate and contract with the Los Angeles County Flood Control District, the West Basin Municipal Water District, and any other public or private corporation or agency to the purpose of this act."

The former State Water Resources Board, in order to implement the intent of this legislation, contracted with the Los Angeles County Flood Control District, University of California, and United States Geological Survey, Quality of Water Branch, for certain basic portions of this investigational program. The California Department (then Division) of Water Resources, acting as the engineering staff for the State Water Resources Board, coordinated and supervised the investigational program. At the same time, the Department of Water Resources augmented this experimental program under authority of Section 229 of the Water Code, which directs that the Department shall:

> ". . . investigate conditions of the quality of all waters within the State, including saline waters, coastal and inland, as related to all sources of pollution of whatever nature . . ."

This augmentation consisted primarily of geologic and hydrologic studies of coastal ground water basins.

RELATED INVESTIGATIONS AND REPORTS

Numerous studies and investigations pertaining to sea-water intrusion in California and in other critical areas throughout the United States have been made in the past. A bibliography of these projects is given in Appendix A of this report entitled, "Status of Sea-Water Intrusion" and in Appendix C, Part III, entitled "An Abstract of Literature Pertaining to Sea-Water Intrusion and its Control."

Numerous reports of prior investigations containing information pertinent to the evaluation of the status of sea-water intrusion in California, and to determination of plans and design criteria for correction or prevention of damage to underground waters by sea-water intrusion were referred to in connection with the current investigation. Prominent among these are State Water Resources Board Bulletins No. 5 "Santa Cruz-Monterey Counties Investigation"; No. 7, "Santa Clara Valley Investigation"; No. 12 "Ventura County Investigation"; No. 13 "Alameda County Investigation"; and No. 19 "Salinas River

Basin Investigation." The investigation directed by the court in the case of California Water Service Company vs. City of Compton, results of which were published as "West Coast Basin Reference—Report of Referee," by the California Department of Public Works also provided valuable data. Reports by the United States Geological Survey on Petaluma Valley, Napa-Sonoma Valley, and the coastal plain areas of Los Angeles and Orange Counties were also utilized.

References utilized in this investigation are designated in the text by superscripts and are listed at the end of this report.

SCOPE OF INVESTIGATION AND REPORT

In order to carry out the legislative intent, the State Water Resources Board on July 6, 1951, requested that the Division of Water Resources investigate and submit recommendations for an experimental program for the prevention and control of sea-water intrusion. These recommendations, contained in a report entitled "Proposed Investigational Work for Control and Prevention of Sea-Water Intrusion into Ground Water Basins," dated August, 1951, were as follows:

1. An allocation of $30,000 should be made from funds presently available, for laboratory research and investigations of certain basic factors involved in sea-water intrusion and means for its prevention. Such research program should be undertaken by one of the large universities having adequate hydraulic laboratory facilities. Work should be started immediately and run concurrently with field experimentation, with results and data interchanged as quickly as they become available.

2. The sum of $450,000 should be allocated, from funds presently available, for installation and one year's operation of a field experimental project to investigate the hydraulic feasibility of creating a pressure ridge in confined aquifers by means of injection wells and the effectiveness of such a ridge in preventing sea-water intrusion. This project should be undertaken in the vicinity of Manhattan Beach in West Coast Basin, Los Angeles County. The initial installation should comprise five injection wells and sufficient observation wells to yield the observational data necessary for complete and conclusive interpretation of the results. Capital cost for feeder and distribution pipe lines should be kept to a minimum and emphasis placed upon experimental techniques and collection of pertinent data so that the results and conclusions will be applicable on a state-wide basis.

3. Additional funds should be allocated to the Manhattan Beach field experiment if results of the first six months operation, analyzed in conjunction with laboratory research studies, indicate that the initial installation of five injection wells is not extensive enough to yield conclusive results.

4. If the pressure ridge is found to be hydraulically feasible and effective in the prevention of sea-water intrusion and if funds are then available, a field experimental project should be undertaken to determine the feasibility of maintaing such a ridge with reclaimed water. The experiment could be conducted near the Hyperion sewage treatment plant of the City of Los Angeles or at other suitable locations using the effluent therefrom; estimated cost—$300,000.

5. No field experimental work using injected materials or other techniques to reduce the permeability of aquifers as a means of preventing sea-water intrusion should be undertaken until results of the laboratory research recommended in paragraph 1 above are available and the possible application of the various methods and materials can be judged therefrom.

6. The State Water Resources Board and its staff should further investigate and study the techniques of construction and results achieved in actual installations of the puddled clay and similar types of cutoff walls, before a decision is made as to the desirability or necessity for a field experimental project using subsurface barriers of this type. If such a field experimental project is found advisable, it should be done either at the mouth of San Luis Rey Valley or along the coast in Orange County.

7. The State Water Resources Board should carefully supervise the planning and execution of all experimental work, in order to assure that the results obtained therefrom are interpretable and usable on a state-wide basis.

8. Upon conclusion of the experimental program, the State Water Resources Board and its staff should study and report upon the economic factors and considerations involved in prevention of sea-water intrusion.

In order to implement this comprehensive investigational program the State Water Resources Board contracted with various agencies, as previously mentioned, for certain basic portions thereof. At the same time a comprehensive study was initiated of the current status of sea-water intrusion in some 260 ground water basins bordering the coast of California, and of the geologic and hydrologic characteristics of these basins.

The State Water Resources Board allocated $642,000 to the Los Angeles County Flood Control District to study the hydraulic feasibility of creating a pressure ridge in confined aquifers by means of injection wells, and the effectiveness of such a ridge in preventing sea-water intrusion. The District constructed and operated large scale experimental recharge facilities in the Manhattan Beach-Hermosa Beach area as part of this study. State funds were exhausted in December, 1953; and the District has since continued operation on a reduced scale, using its own and local funds.

Funds for laboratory studies were also made available to the University of California to supplement this field experiment. Model studies of basic parameters of sea-water intrusion and studies of methods of reduction of aquifer permeability were conducted by the University of California at the Sanitary Engineering Research Field Station, Richmond, California. A comprehensive survey and abstract of literature pertaining to sea-water intrusion was completed by the University.

Laboratory studies were also conducted at the Department of Engineering of the University of California at Los Angeles, to determine the compatibility of Colorado River water purchased from the Metropolitan Water District of Southern California with ground waters in the Silverado water-bearing zone of the West Coast Basin.

Chemical analyses of numerous samples of ground water at the site of the West Coast Basin field test were made by the United State Geological Survey at Sacramento, California, to study the geochemistry of the ground water and to determine whether salt-water intrusion in the test area was due to ingress of sea water, oil field brines, connate water, or a combination thereof.

Results of this investigation are presented in this report in the seven ensuing chapters. Chapter II, "Physical Characteristics of Sea-Water Intrusion Into Aquifers," discusses fresh water-salt water density relationships, including the Ghyben-Herzberg principle and sea-water wedge, as well as the geologic and hydrologic conditions in coastal ground water basins under which sea-water intrusion may occur. Chapter III, "Present Status of Sea-Water Intrusion in California," evaluates the status of sea-water intrusion in California and discusses increased ground water salinity from causes other than sea-water intrusion. It also includes a detailed description of critical areas throughout the State. Chapter IV, "Methods of Control of Sea-Water Intrusion," describes five major methods of control and prevention of intrusion and presents basic cost data. Chapter V. "Experimental Studies Pertinent to the Sea-Water Intrusion Problem," evaluates prior and current studies pertaining to injection wells, surface spreading, subsurface barriers, and other techniques which might be utilized in preventing and controlling sea-water intrusion. It also includes a detailed study and evaluation of the experimental studies which were performed by the Los Angeles County Flood Control District, University of California, and United States Geological Survey. Economic and legal aspects are discussed in Chapter VI, "Economic and Legal Considerations." Chapter VII, "Plans for Prevention and Control of Sea-Water Intrusion," describes plans for control of sea-water intrusion. Chapter VIII, "Conclusions and Recommendations," includes the conclusions and recommendations resulting from the investigation and studies.

This report is augmented by five appendixes. Appendix A contains detailed tabulations of the status of sea-water intrusion into coastal ground water basins, including geology and typical analyses of surface and ground waters; Appendix B presents the report of the Los Angeles County Flood Control District; Appendixes C and D present the reports of the University of California and University of California at Los Angeles, respectively; and Appendix E is the report of the United States Geological Survey, Quality of Water Branch.

AREA UNDER INVESTIGATION

The area under investigation encompasses all ground water basins in California bordering the coast and saline inland bays. Particularly intensive field experiments were conducted in a portion of West Coast Basin, Los Angeles County, in connection with an investigation of the feasibility of establishing a pressure ridge in a confined aquifer. Locations of these areas are delineated on Plate 1, "Area of Investigation."

DEFINITIONS

In this report, certain terminology and concepts relating to geology, hydrology, and water quality are utilized with specific connotations. In order to facilitate the reader's understanding of the material contained herein, and avoid ambiguities and misconceptions regarding interpretation of these terms, the following definitions are presented:

Alluvium—A general term for stream deposited sedimentary materials, usually of recent geologic age.

Aquifer—A formation sufficiently permeable to yield water to wells or springs.

Fault—A fracture or fracture zone along which there has been relative displacement of the two sides parallel to the fracture.

Geologic Formation—Any assemblage of rocks which have some character in common, whether of origin, age, or composition.

Artesian Well—A well tapping a confined or artesian aquifer i.e., one in which the static water level rises above the top of the water-bearing body.

Confined Ground Water—A body of ground water overlain by material sufficiently impervious to sever free hydraulic connection with overlying water. Confined water moves under pressure due to difference in head between the intake or forebay area and the discharge area of the confined water body.

Connate Water—Fresh, brackish, or saline water entrapped in the interstices of a sedimentary rock at the time of deposition.

Free Ground Water—Ground water in the zone of saturation that is not confined beneath an impervious formation.

Ground Water Overdraft—The rate of net extraction of water from a ground water basin in excess of safe ground water yield.

Ground Water Pressure Surface or Level—An imaginary surface connecting points to which confined ground water will rise in non-pumping wells which pierce an artesian or confined aquifer (synonymous with piezometric surface).

Perched Ground Water—Ground water occurring in a saturated upper zone separated from the main body of ground water by impervious material.

Permeability Coefficient—The rate of flow of water in gallons per day and at 60° F. through a cross section of an aquifer one square foot in area under a unit (100 per cent) hydraulic gradient.

Piezometric Surface—Synonymous with ground water pressure surface.

Safe Ground Water Yield—The maximum rate of net extraction of water from a ground water basin which can be continued over an indefinitely long period without eventually bringing about undesirable results. Commonly, safe ground water yield is determined by one or more of the following criteria:

1. Mean annual extraction of water from the ground water basin does not exceed mean annual replenishment to the basin.
2. Water levels are not so lowered as to cause harmful impairment of the quality of the ground water by intrusion of other water of undesirable quality, or by accumulation and concentration of degradants or pollutants.
3. Water levels are not so lowered as to imperil the economy of ground water users by excessive costs of pumping from the ground water basin, or by exclusion of users from a supply therefrom.
4. Prior rights of others in adjacent ground water basins are not interfered with.

Transmissibility Coefficient—The rate of flow of water through an aquifer, in gallons per day, at the prevailing water temperature, through a vertical strip of the aquifer one foot wide having a height equal to the thickness of the aquifer and under a unit (100 per cent) hydraulic gradient.

Water Table—The upper surface of a free ground water body.

Chemical Classification of Waters — Waters are classified, with respect to mineral composition, in terms of the predominant ions. Specifically, the name of an ion is used where it constitutes at least half of its ionic group, expressed in equivalent weights. Where no one ion fulfills this requirement, a hyphenated combination of the two most abundant constituents is used. Thus a calcium bicarbonate water denotes that calcium constitutes at least half of the cations and bicarbonate represents at least half of the anions. Where calcium, though predominant, is less than half, and sodium next in abundance, the name is modified to calcium-sodium bicarbonate.

Contamination—As defined in Section 13005 of the Water Code "Contamination means an impairment of the quality of the waters of the State by sewage or industrial waste to a degree which creates an actual hazard to public health through poisoning or through the spread of disease . . ." Jurisdiction over matters regarding contamination rests with the State Department of Public Health and local health officers.

Degradation—Impairment in the quality of water due to causes other than disposal of sewage and industrial waste, such as sea-water intrusion, adverse salt balance, lateral and/or vertical diffusion of connate brines, etc. No direct, definite means of prevention and control are available under present law; but one of the basic statutory responsibilities of the Department of Water Resources is to investigate these problems and report thereon with recommendations to the Legislature and Regional Water Pollution Control Boards (Sec. 229 Water Code).

Pollution—As defined in Section 13005 of the Water Code. "Pollution means an impairment of the quality of the waters of the State by sewage or industrial waste to a degree which does not create an actual hazard to the public health but which does adversely and unreasonably affect such waters for domestic, industrial, agricultural, navigational, recreational or other beneficial use, . . ." Regional Water Pollution Control Boards are responsible for prevention and abatement of pollution as defined in this section.

However, the Attorney General has stated that the term "pollution" as used in Section 229 of the Water Code, which relates to investigations of water quality by the Department of Water Resources, is general in nature. Thus, with respect to this study, it encompasses all types of water quality deterioration, including sea-water intrusion and other types of degradation.

Quality of Water—Those physical, chemical, and biological characteristics of water that affect its suitability for beneficial use.

Salt Balance—Relationship of salt input to salt output in a hydrologic unit. A favorable balance exists when salt output equals or exceeds input. Where the total quantity of salts entering the unit exceeds the quantity leaving the unit, an accumulation of salts occurs within the unit, and an adverse salt balance exists.

WATER QUALITY CRITERIA

The suitability of waters for beneficial use, and the effect thereon of sea-water intrusion, can best be determined by consideration of water quality requirements. Presented herein are general criteria and limiting values presently used by the Department of Water Resources in evaluating and classifying water quality. In general, these values should be considered only as guides and indicators, and not as absolute limitations.

LIMITING CONCENTRATIONS OF MINERAL CONSTITUENTS FOR DRINKING WATER

U. S. Public Health Service
Drinking Water Standards, 1946
in parts per million

Constituent	Limit
Mandatory limits	
Fluoride (F)	1.5
Lead (Pb)	0.1
Selenium (Se)	0.05
Hexavalent chromium (Cr^{+6})	0.05
Arsenic (As)	0.05
Nonmandatory but recommended limits	
Iron (Fe) and Manganese (Mn) together	0.3
Magneisum (Mg)	125
Chloride (Cl)	250
Sulfate (SO_4)	250
Copper (Cu)	3.0
Zinc (Zn)	15
Phenolic compounds in terms of phenols	0.001
Total solids	
Desirable	500
Permitted	1,000

The standards promulgated by the United States Public Health Service, listed on the left, have been widely adopted as definitive criteria for domestic water supplies.

In addition to these constituents, other organic or mineral compounds must be considered if their presence in the water renders it unsatisfactory for use.

Hardness of water is of importance in domestic and industrial use. The United States Geological Survey has suggested the following four classes of degree of hardness:

HARDNESS CLASSIFICATION OF WATERS

U. S. Geological Survey
in parts per million

Class	Range of hardness	Degree
1	0–55	Soft
2	56–100	Slightly hard
3	101–200	Moderately hard
4	201–500	Very hard

The suitability of water for irrigation use varies throughout the State, because of the great diversity of climatic conditions, crops, soils, and irrigation practices encountered in California. A suggested classification of irrigation waters, which must of necessity be general in nature, follows:

QUALITATIVE CLASSIFICATION OF IRRIGATION WATERS

Chemical properties	Class 1 (Suitable for most plants under any conditions of soil and climate) Excellent to good	Class 2 (Possibly harmful for some crops under certain conditions) Good to injurious	Class 3 (Harmful to most crops and unsatisfactory for all but the most tolerant) Injurious to unsatisfactory
Total dissolved solids			
In ppm	Less than 700	700–2,000	More than 2,000
In conductance EC × 10^6	Less than 1,000	1,000–3,000	More than 3,000
Chloride ion concentration			
In milliequivalents per liter	Less than 5	5–10	More than 10
In ppm	Less than 175	175–350	More than 350
Sodium in per cent of base constituents	Less than 60	60–75	More than 75
Boron in ppm	Less than 0.5	0.5–2.0	More than 2.0

(Adapted from the report by Wilcox, L. V. and Magistad, O. C., "Interpretation of Analyses of Irrigation Waters and the Relative Tolerance of Crop Plants," United States Department of Agriculture, Bureau of Plant Industry, Soils and Agricultural Engineering. May 1943.)

Water quality requirements for industrial use range from the exacting demands of boiler make-up water to the relatively high tolerances of water used for washdown and metallurgical processing. The following tabulation shows general quality requirements for various industrial uses, as suggested in "Progress Report of the Committee on Quality Tolerance of Water for Industrial Uses," Journal of the New England Water Works Association, 1940.

WATER QUALITY TOLERANCE FOR INDUSTRIAL USES[a]

Allowable limits in parts per million

Use	Turbidity	Color	Hardness as $CaCO_3$	Iron[c] as Fe	Manganese as Mn	Total solids	Alkalinity as $CaCO_3$	Odor, taste	Hydrogen sulfide	Miscellaneous requirements: Health	Miscellaneous requirements: Other
Air conditioning	--------	--------	--------	0.5	0.5	--------	--------	Low	1	--------	No corrosiveness, slime formation
Baking	10	10	--------	0.2	0.2	--------	--------	Low	0.2	Potable[b]	
Brewing											
Light beer	10	--------	--------	0.1	0.1	500	75	Low	0.2	Potable[b]	NaCl less than 275 ppm (pH 6.5-7.0).
Dark beer	10	--------	--------	0.1	0.1	1,000	150	Low	0.2	Potable[b]	NaCl less than 275 ppm (pH 7.0 or more)
Canning											
Legumes	10	--------	25–72	0.2	0.2	--------	--------	Low	1	Potable[b]	
General	10	--------	--------	0.2	0.2	--------	--------	Low	1	Potable[b]	
Carbonated beverages	2	10	250	0.2	0.2	850	50–100	Low	0.2	Potable[b]	Organic color plus oxygen consumed less than 10 ppm.
Confectionary	--------	--------	--------	0.2	0.2	100	--------	Low	0.2	Potable[b]	pH above 7.0 for hard candy.
Cooling	50	--------	50	0.5	0.5	--------	--------	--------	5	--------	No corrosiveness, slime formation.
Food: General	10	--------	--------	0.2	0.2	--------	--------	Low	--------	Potable[b]	
Ice	5	5	50	0.2	0.2	--------	--------	Low	--------	Potable[b]	SiO_2 less than ppm.
Laundering	--------	--------	50	0.2	0.2	--------	--------	--------	--------	--------	
Plastics, clear, uncolored	2	2	--------	0.02	0.02	200	--------	--------	--------	--------	
Paper and pulp:											
Groundwood	50	20	180	1.0	0.5	--------	--------	--------	--------	--------	No grit, corrosiveness.
Kraft pulp	25	15	100	0.2	0.1	300	--------	--------	--------	--------	
Soda and sulfide	15	10	100	0.1	0.05	200	--------	--------	--------	--------	
High-grade light papers	5	5	50	0.1	0.05	200	--------	--------	--------	--------	
Rayon (viscose):											
Pulp production	5	5	8	0.05	0.03	100	total 50; hydroxide 8	--------	--------	--------	Al_2O_3 less than 8 ppm, SiO_2 less than 25 ppm, Cu less than 5 ppm.
Manufacture	0.3	--------	55	0.0	0.0	--------	--------	--------	--------	--------	pH 7.8 to 8.3
Tanning	20	10–100	50–135	0.2	0.2	--------	total 135; hydroxide 8	--------	--------	--------	
Textiles: General	5	20	--------	0.25	0.25	--------	--------	--------	--------	--------	
Dyeing	5	5–20	--------	0.25	0.25	200	--------	--------	--------	--------	Constant composition. Residual alumina less than 0.5 ppm.
Wool scouring	--------	70	--------	1.0	1.0	--------	--------	--------	--------	--------	
Cotton bandage	5	5	--------	0.2	0.2	--------	--------	Low	--------	--------	

[a] Moore, E. W., Progress Report of the Committee on Quality Tolerances of Water for Industrial Uses: Journal of New England Water Works Association, Volume 54, page 271, 1940.

[b] Potable water, conforming to U. S. P. H. S. standards, is necessary.

[c] Limit given applies to both iron alone and the sum of iron and manganese.

CHAPTER II

PHYSICAL CHARACTERISTICS OF SEA-WATER INTRUSION INTO AQUIFERS

Intrusion of sea water into aquifers is governed by physical laws which are relatively simple in theory but difficult to apply because of the inherent complexities of ground water basins. Conditions prerequisite to sea-water intrusion and the laws governing its occurrence and behavior are presented herein.

PREREQUISITE CONDITIONS

From a practical standpoint, there are two fundamental conditions which must exist before a ground water basin can be intruded by sea water. First, the water-bearing materials comprising the basin must be in hydraulic continuity with the ocean; and second, the normal seaward ground water gradient must be reversed, or at least be too flat to counteract the greater density of sea water.

Geologic Conditions

Ground water supplies in coastal basins in California are stored mainly in the larger alluvium-filled valleys. These valley fill areas, which are of variable depth, are composed of unconsolidated alluvial fan, flood plain, and shallow marine deposits. Extensive sand and gravel deposits occur in the large coastal plain areas in Orange, Los Angeles, Ventura, Monterey, Santa Clara, Napa, and Sonoma Counties. These deposits extend to many hundreds of feet below sea level along the coast, and may extend for some distance beneath the floor of the Pacific Ocean and under San Francisco Bay.

In addition to the extensive ground water supplies in these large coastal plain areas, limited quantities of ground water occur in numerous shallow alluvium-filled valleys along the coast. These small valleys, and the several known buried channels filled with sand and gravel, represent buried coarse-grained deposits in ancestral channels of Pleistocene streams. The base of these old buried stream channels adjacent to the coast is quite shallow, generally 150-200 feet below sea level. In a few isolated areas, however, the base approaches 300 feet below sea level.

Geologic evidence indicates that the water-bearing deposits along the seaward and bayward margins of these coastal ground water basins either may be in direct contact with the ocean or bay floor at the shoreline, or may extend beneath the floor as confined pressure aquifers in contact with sea water at some distance offshore. Numerous submarine canyons are incised into the continental shelf, resulting in relatively close-in exposure of the fresh-water-bearing sediments to sea water.

Hydraulic Conditions

Sea-water intrusion can occur only when the pressure head of sea water exceeds that of the fresh ground water, a condition which usually results when ground water levels are lowered to or below sea level by excessive pumping of wells. When the hydraulic gradient within a coastal basin slopes seaward, ground water is moving toward the ocean; and conversely when the slope is reversed, sea water is moving landward. It should be noted that under extremely small seaward gradients of the fresh water, both conditions can exist simultaneously. In practice, the slope of the hydraulic gradient is established from measurements of depth to water in observation wells.

FRESH WATER-SALT WATER RELATIONSHIPS

Fresh water weighs less than sea water. Therefore, when the two come in contact within a permeable formation, there is a tendency for the lighter fresh water to float on the heavier sea water. This phenomenon can be demonstrated by a simple laboratory apparatus in which a tube containing loose sand is partially immersed in ocean water and then filled from the top with fresh water. Under these idealized conditions, the fresh water displaces ocean water from the sand and floats upon it much as a solid buoyant object floats on water. The presence of the sand greatly impedes diffusion of the two liquids which would otherwise occur almost instantaneously. The floating body of fresh water in this example conforms to Archimedes law of buoyancy which states that any floating object will displace its own weight of the medium in which it floats. This principle, as applied to relationships between fresh and sea water, is commonly known as the Ghyben-Herzberg Principle. It was described by Badon Ghyben in 1889, and applied to water supply problems by Bairat Herzberg in 1901.

Since sea water weighs 1.025 times as much as fresh water, the relationship between water table elevation above sea level (T) and depth to sea-water interface (H) may be developed by simple algebra as follows:

$$(H + T) = 1.025H$$

$$T = 1.025H - H$$

$$T = H(1.025 - 1)$$

$$T = 0.025H$$

$$T = \frac{1}{40}H \qquad (1)$$

Equation (1) indicates that a body of fresh water floating upon sea water within a porous medium adjusts in elevation until the depth of its lower surface, measured below sea level datum, is 40 times the height of its upper surface above this datum. Thus the floating body assumes a shape such that its depth below sea level is everywhere 40 times its surface elevation above sea level.

THE SEA-WATER WEDGE

The theoretical sea-water front assumes the shape of an inclined surface which always slopes landward, and which advances or recedes in response to changes in the hydraulic gradient. Because of its shape, this prism of ocean water has been called the sea-water wedge. Plate 2 depicts a diagrammatic section through a coastal basin for both confined and unconfined aquifers. Condition I depicts a seaward sloping hydraulic gradient, whereas Condition II represents a landward sloping hydraulic gradient. It follows from elementary hydraulics that under these conditions the hydraulic gradient must meet sea level at the point where the aquifer attains hydraulic continuity with the ocean, and consequently both H and T of equation (1) become zero at this point. In an unconfined aquifer under Condition I, the sea-water interface must therefore intersect ground water surface at the shore line.

Advance and retreat of the wedge commences at the toe, the position of the upper end of the interface remaining fixed at the shore line until all fresh water near the coast is depleted to sea level, at which time the upper end of the interface commences its advance and the entire wedge moves as a body. If on its landward advance, the toe of the wedge extends into a water table depression, an upwelling of sea water occurs. The configuration of this upwelling conforms to the dictates of equation (1). Where the depression is conical, as in the case created by a pumping well, the upwelling assumes the shape of an image cone, the surface of which theoretically becomes 40 times as steep as the sides of the overlying pumping depression.

The sea-water wedge also forms in pressure aquifers, as indicated in the schematic illustrations of Plate 2. By reasoning similar to that developed in the preceding paragraphs, it can be demonstrated that the relationship $H = 40T$ also holds true for pressure conditions; however, in this case, the corollary that the interface intersects land surface at the shore line is not necessarily valid.

Parameters governing intrusion characteristics of a sea-water wedge were developed at the University of California from construction, operation, and study of a scale model. Results of this investigation are presented at length in Appendix C to this report, and are briefly summarized in Chapter V.

OTHER CAUSES OF INCREASED GROUND WATER SALINITY

An increase in the salinity of ground water within a coastal basin does not necessarily establish the existence of sea-water intrusion. Such increases may be attributable entirely or in part to other factors. Some of the more significant causes of ground water degradation other than sea-water intrusion, illustrated schematically on Plate 3, include the following:

1. Degradation of ground water through its use and re-use. Without sufficient outflow, this may result in adverse salt balance.
2. Degradation through lateral or upward migration of brines or degraded waters contained in the formations flanking or underlying the ground water basin.
3. Degradation through downward seepage of sewage or industrial waste.
4. Degradation through downward seepage of mineralized surface waters from streams, lakes and lagoons.
5. Degradation through the migration of saline water from one water-bearing zone to another either through natural breaks in impermeable layers or through defective, improperly constructed, or abandoned wells.

It is sometimes difficult to fix the true causes for rises in salinity of ground water. Before sea-water intrusion can be definitely established as the cause, it must be shown that there is evidence of hydraulic continuity with the ocean, a landward sloping hydraulic gradient has prevailed, and progressive degradation of ground water quality has occurred adjacent to the ocean or bay. Even in the presence of these conditions, it is possible under certain circumstances that the salinity rise may be due to some other cause, as previously mentioned. In such instances, chemical analyses and the ratios of certain constituent ions may prove helpful in identifying sea water. However, it is to be noted that with present knowledge, it is exceedingly difficult, if not impossible, to distinguish sea water from certain oil field brines or connate waters by means of chemical analyses. A need for additional research in this field is clearly indicated.

APPLICABILITY TO EXISTING CONDITIONS

In California, the deep aquifers of many ground water basins extend offshore, in some instances for several miles. Many of these extensions are overlain by materials of low permeability, and are in contact with the ocean only at their seaward extremities. Under conditions of surplus ground water supply and seaward sloping hydraulic gradients, these extensions transmit fresh water to the ocean under artesian pressure. The quantity of fresh water stored offshore within the extensions is often considerable. The effect of this offshore storage is to postpone the arrival of sea water into the basin proper until long after landward sloping hydraulic gradients are established. In certain instances, ground water levels in confined aquifers have been lowered and maintained below sea level for lengthy periods without chemical evidence of sea-water intrusion becoming apparent. At West Coast Basin near Wilmington and at Goleta Basin near Santa Barbara, fresh-water levels have dropped to 104 and 70 feet below sea level respectively and have remained below sea level for many years with no chemical evidence of intrusion. In these and other similar instances, it is exceedingly difficult to determine whether sea-water intrusion is being delayed due to the effects of offshore storage or whether hydraulic connection between the aquifers and ocean is poor or non-existent. Obviously, the transmissibilities and storage capacities of the seaward extensions of pressure aquifers are not amenable to accurate determination. Because of such complexities, the application of theoretical equations to the estimation of rate of intrusion, or to the prediction of the time of arrival of the sea-water interface, is generally difficult and uncertain.

The sediments comprising free ground water aquifers generally occur as interfingering lenses of fine and coarse sediments. Sea water advances more rapidly through the coarser, more permeable members, and less rapidly through the finer deposits. Thus, sea-water intrusion ordinarily does not advance as a uniform sloping front as assumed in most theoretical discussions.

Generally, the ocean floor slopes gently along the shore. Consequently, deep gravel beds are exposed at greater distance offshore than are shallow beds, and the paths traversed by sea water through the beds, from point of exposure on the ocean floor to shore line, are shorter for the shallower beds. Because of this condition, intrusion may first become evident at shallow depth, contrary to the dictates of the theoretical laws governing the sea-water wedge.

Often, shallow sediments for some distance inland are saturated with sea water by percolation of tidal waters from sloughs. In these instances the theoretical sea-water wedge does not develop.

In regard to changes in configuration of the sea-water interface in response to water table fluctuations, it is reiterated that these responses are generally slow. When wells are pumped, the water table is generally quickly depressed. However, equilibrium in the fresh-salt water interface may be attained only if these pumping depressions are maintained for long periods. Because of this time lag, the depth to the interface can rarely be determined through application of equation (1).

In brief, theoretical concepts assist in comprehension of the mechanics of sea-water intrusion. However, due to inherent complexities of ground water conditions, an academic approach to problems in this field is applicable only in those rare instances in which conditions are relatively simple and straightforward.

CHAPTER III

PRESENT STATUS OF SEA-WATER INTRUSION IN CALIFORNIA

This chapter summarizes the current status of sea-water intrusion into ground water basins bordering the California coast and inland bays. Along the coast, 262 ground water basins have been identified in which water-bearing deposits are apparently open to the ocean or to saline inland bays. All of these basins must be considered as potential areas for intrusion of sea water.

These 262 ground water basins are grouped into the following four categories with respect to the present status of sea-water intrustion therein, as determined from data available:

(1) Areas of known sea-water intrusion
(2) Areas of suspected sea-water intrusion and areas where chlorides in the ground waters exceed 100 parts per million
(3) Areas of no apparent sea-water intrusion
(4) Areas where the status of sea-water intrusion is unknown

The status of sea-water intrusion into ground water basins bordering the California coast is shown in Table 1 and Plate 4. Comprehensive descriptions of all coastal ground water basins are presented in Appendix A.

AREAS OF KNOWN SEA-WATER INTRUSION

Existence of all of the following characteristics and conditions is presumed to constitute positive evidence of the intrusion of sea water:

(1) Water-bearing deposits at the coast line extend to considerable depths below sea level;
(2) Water-bearing deposits are either in direct contact with the ocean or bay floor, or they extend beneath the floor as confined pressure aquifers and at some distance offshore may be in contact with sea water;
(3) There is moderate to extensive development of ground water;
(4) Ground water levels in the coastal areas have been below sea level for considerable periods of time, and the normal seaward hydraulic gradient has been reversed so that ground water moves inland from the coast;
(5) Coastal ground waters now contain chlorides in excess of 100 parts per million and these high chloride waters are moving landward in the direction of the reversed hydraulic gradient.

As of 1957, sea-water intrusion was a critical water quality problem in nine coastal ground water basins (see Plate 4 and Table 1). The most serious invasion has occurred in the overdrawn West Coast Basin in Los Angeles County, where intrusion was first noted in 1912, and in the adjacent East Coastal Plain Pressure Area in Orange County. Draft on ground water supplies exceeds replenishment in these basins; water levels are and have been for some years, below sea level; the ground water gradients slope inland to pumping troughs; and there are no continuous barriers in the aquifers to landward movement of saline water.

Other critical areas in which sea water has encroached include: (1) Petaluma Valley in Sonoma County; (2) Napa-Sonoma Valley in Napa and Sonoma Counties; (3) Santa Clara Valley in the San Francisco Bay Area; (4) Pajaro Valley in Monterey and Santa Cruz Counties; (5) Salinas Valley Pressure Area in Monterey County; (6) Oxnard Plain Basin in Ventura County; and (7) Mission Basin in San Diego County. Draft on ground water supplies in these basins exceeds replenishment, especially during the critical summer months.

Continued pumping at present rates will allow further encroachment of sea water into these basins. In addition to direct encroachment of sea water into fresh water-bearing deposits, intrusion may now be occurring, or may occur in the future, in these areas due to percolation of saline or brackish perched or tidal waters through natural or man-made breaks in the clay layers overlying pressure aquifers.

The nine areas where sea-water intrusion is known to have occurred are discussed in detail later in this chapter, and plans for correction and prevention of intrusion are presented in Chapter VII.

AREAS OF SUSPECTED SEA-WATER INTRUSION AND AREAS WHERE CHLORIDES EXCEED 100 PARTS PER MILLION

Sea-water intrusion is thought to account for the observed deterioration in quality of the coastal ground waters, in most instances, where the following conditions exist. Although other causes may also be operative, the available data are inadequate for a positive determination as to cause:

(1) Water-bearing deposits at the coast line apparently extend below sea level and are open to the ocean;

TABLE 1

STATUS OF SEA-WATER INTRUSION INTO GROUND WATER BASINS BORDERING THE CALIFORNIA COAST AND INLAND BAYS

*Index No.	†Ground water basin No.	Ground water basin or valley	County
		Areas of known sea-water intrusion	
87	2-1	Petaluma Valley	Sonoma and Marin
88	2-2	Napa-Sonoma Valley	Napa and Sonoma
105	2-9	Santa Clara Valley	Alameda, Santa Clara and San Mateo
147	3-2	Pajaro Valley	Santa Cruz and Monterey
149	3-4.01	Salinas Valley Pressure Area	Monterey
218	4-4.01	Oxnard Plain Basin	Ventura
234	4-11.02	West Coast Basin	Los Angeles
235	8-1.01	East Coastal Plain Pressure Area	Orange
243		Mission Basin	San Diego
		Areas of suspected sea-water intrusion and areas of over 100 ppm chloride	
6		Redwood Creek Basin	Humboldt
11	1-8	Mad River Valley	Humboldt
12	1-9	Eureka Plain	Humboldt
13	1-10	Eel River Valley	Humboldt
57		Russian River Basin	Sonoma
60		Bodega Bay Basin	Sonoma
77		Frank Creek Basin	Marin
83		San Rafael Basin	Marin
86		Novato Valley Basin	Marin
89		Southampton Bay Basin	Solano
90		Benicia Basin	Solano
92	2-3	Suisun-Fairfield Valley	Solano
93		Sacramento-San Joaquin Delta	Solano, Sacramento, San Joaquin and Contra Costa
94	2-5, 2-6	Clayton-Ygnacio Valley	Contra Costa
110		Market Street Basin	San Francisco
113		Sharp Park Terrace	San Mateo
118		Half Moon Bay Terrace	San Mateo
120		San Gregorio Creek Basin	San Mateo
127		Scott Creek Basin	Santa Cruz
150		Monterey Area	Monterey
158		Arroyo del Corral Basin	San Luis Obispo
163		Villa Basin	San Luis Obispo
165		Cayucos Point Basin	San Luis Obispo
166		Cayucos Basin	San Luis Obispo
167		Little Cayucos Basin	San Luis Obispo
170		Toro Basin	San Luis Obispo
171		Morro Basin	San Luis Obispo
172		Chorro Basin	San Luis Obispo
175		Pismo Basin	San Luis Obispo
178		Schumann Canyon Basin	Santa Barbara
180		Lompoc Plain	Santa Barbara
185		Cojo Basin	Santa Barbara
195		Gaviota Basin	Santa Barbara
196		Cementario Basin	Santa Barbara
200		Tajiguas Basin	Santa Barbara
201		Canada del Refugio Basin	Santa Barbara
202		Canada del Corral Basin	Santa Barbara
204		Las Varas Basin	Santa Barbara
208		Bell Canyon Basin	Santa Barbara
209		Campbell Creek Basin	Santa Barbara
210	3-16	Goleta Basin	Santa Barbara
211		Hope Basin	Santa Barbara
215	3-18	Carpinteria Basin	Santa Barbara
216	4-3	Ventura River Valley	Ventura
219		Big Sycamore Basin	Ventura
223		Zuma Canyon Basin	Los Angeles
224		Ramera Basin	Los Angeles
228		Malibu Basin	Los Angeles
229		Las Flores Basin	Los Angeles
233	4-11.01	West Coastal Plain-North	Los Angeles
237		Laguna Canyon Basin	Orange
238		Aliso Basin	Orange
239	9-1	San Juan Valley	San Diego
241	9-3	San Onofre Valley	San Diego
242		Santa Margarita Coastal Basin	San Diego
244		Loma Alta Basin	San Diego
245		Buena Vista Creek Basin	San Diego
246		Agua Hedionda Basin	San Diego
247		Encinas Basin	San Diego
248		San Marcos Basin	San Diego
249		San Elijo Basin	San Diego
250	9-12	San Dieguito Valley	San Diego
		Areas of suspected sea-water intrusion and areas of over 100 ppm chloride—continued	
251		Soledad Basin	San Diego
253		Rose Canyon Basin	San Diego
254		Tecolote Creek Basin	San Diego
255	9-14	Mission Valley Basin	San Diego
256		Las Chollas Basin	San Diego
259		Paradise Basin	San Diego
260	9-17	Sweetwater Valley	San Diego
261	9-18	Otay Valley	San Diego
262	9-19	Tia Juana Basin	San Diego
		Areas of no apparent sea-water intrusion	
1	1-1	Smith River Plain	Del Norte
4		Lower Klamath River Basin	Del Norte
7		McDonald Creek Basin	Humboldt
22		Cottoneva Creek Basin	Mendocino
49		Garcia River Basin	Mendocino
64		Walker Creek Basin	Marin
65		Tomales Bay Basin	Marin
67		Point Reyes Sand Dunes Area	Marin
70		Drakes Estero Basin	Marin
74		Laguna Ranch Basin	Marin
76		Bolinas Lagoon Basin	Marin
79		Rodeo Lagoon Basin	Marin
81		Richardson Bay Basin	Marin
82		Ross Valley Basin	Marin
85		San Pedro Point Basin	Marin
112		Merced Valley Basin	San Mateo and San Francisco
114		Calera Basin	San Mateo
115		San Pedro Basin	San Mateo
122		Pescadero Basin	San Mateo
141		San Lorenzo River Basin	Santa Cruz
145	3-1	Soquel Valley	Santa Cruz
151	3-7	Carmel Valley	Monterey
152		San Jose Creek Basin	Monterey
154		Big Sur River Basin	Monterey
157		Arroyo de la Cruz Basin	San Luis Obispo
160		Pico Creek Basin	San Luis Obispo
161		San Simeon Basin	San Luis Obispo
162		Santa Rosa Creek Basin	San Luis Obispo
168		Old Creek Basin	San Luis Obispo
173		Los Osos Basin	San Luis Obispo
174		San Luis Obispo Basin	San Luis Obispo
176		Arroyo Grande Basin	San Luis Obispo
177	3-12	Santa Maria River Valley	San Luis Obispo and Santa Barbara
189		San Augustin Basin	Santa Barbara
198		Arroyo Hondo Basin	Santa Barbara
199		Arroyo Quemado Basin	Santa Barbara
203		Capitan Basin	Santa Barbara
205		Dos Pueblos Basin	Santa Barbara
207		Tecolote Basin	Santa Barbara
213	3-17	Santa Barbara Basin	Santa Barbara
217	4-4.03	Mound Basin	Ventura
220		Little Sycamore Basin	Ventura
221		Arroyo Sequit Basin	Los Angeles
222		Trancas Basin	Los Angeles
226		Solstice Basin	Los Angeles
230		Topanga Basin	Los Angeles
236		Sand Canyon Basin	Orange
240	9-2	San Mateo Valley	San Diego
		Areas where the status of sea-water intrusion is unknown	
2		Wilson Creek Basin	Del Norte
3		Cedar Mill Basin	Del Norte
5		Prairie Creek Area	Humboldt
8		Maple Creek Basin	Humboldt
9		Little River Basin	Humboldt
10		Dows Prairie Area	Humboldt
14		Fleener Creek Basin	Humboldt
15		Bear River Basin	Humboldt
16		Singley Creek Terrace	Humboldt
17		Davis Creek Terrace	Humboldt
18		Mattole River Basin	Humboldt
19		Big Flat Creek Basin	Humboldt
20		Jackass Creek Basin	Mendocino

TABLE 1—Continued

STATUS OF SEA-WATER INTRUSION INTO GROUND WATER BASINS BORDERING THE CALIFORNIA COAST AND INLAND BAYS

*Index No.	†Ground water basin No.	Ground water basin or valley	County	*Index No.	†Ground water basin No.	Ground water basin or valley	County
		Areas where the status of sea-water intrusion is unknown—continued				Areas where the status of sea-water intrusion is unknown—continued	
21		Usal Creek Basin	Mendocino	107		Visitation Basin	San Mateo and San Francisco
23		Hardy Creek Basin	Mendocino				
24		Juan Creek Basin	Mendocino	108		Potrero Basin	San Francisco
25		Howard Creek Basin	Mendocino	109		Islais Basin	San Francisco
26		De Haven Creek Basin	Mendocino	111		Fort Mason Basin	San Francisco
27		Wages Creek Basin	Mendocino	116		Montara Terrace	San Mateo
28		Abalobadiah Creek Basin	Mendocino	117		Montara Point Basin	San Mateo
29		Seaside Creek Basin	Mendocino	119		Tunitas Creek Basin	San Mateo
30		Ten Mile River Basin	Mendocino	121		Pomponio Basin	San Mateo
31		Little Valley Area	Mendocino	123		Los Frijoles Basin	San Mateo
32		Mill Creek Basin	Mendocino	124		Whitehouse Creek Basin	San Mateo
33		Pudding Creek Basin	Mendocino	125		Ano Nuevo Terrace	San Mateo
34		Noyo River Basin	Mendocino	126		Wadell Basin	Santa Cruz
35		Hare Creek Basin	Mendocino	128		Molino Creek Basin	Santa Cruz
36		Jug Handle Creek Basin	Mendocino	129		Davenport Landing Basin	Santa Cruz
37		Caspar Creek Basin	Mendocino	130		San Vicente Creek Basin	Santa Cruz
38		Russian Gulch Basin	Mendocino	131		Liddell Creek Basin	Santa Cruz
39		Big River Basin	Mendocino	132		Respini Creek Basin	Santa Cruz
40		Little River Basin	Mendocino	133		Laguna Creek Basin	Santa Cruz
41		Albion River Basin	Mendocino	134		Majors Creek Basin	Santa Cruz
42		Salmon Creek Basin	Mendocino	135		Baldwin Creek Basin	Santa Cruz
43		Navarro River Basin	Mendocino	136		Needle Rock Basin	Santa Cruz
44		Greenwood Creek Basin	Mendocino	137		Sandy Flat Basin	Santa Cruz
45		Elk Creek Basin	Mendocino	138		Meder Creek Basin	Santa Cruz
46		Alder Creek Basin	Mendocino	139		Terrace Basin	Santa Cruz
47		Staramella Ranch Basin	Mendocino	140		Moore Creek Basin	Santa Cruz
48		Brush Creek Basin	Mendocino	142		Arana Gulch Basin	Santa Cruz
50		Point Arena Creek Basin	Mendocino	143		Schwans Lagoon Basin	Santa Cruz
51		Mate Creek Basin	Mendocino	144		Doyle Basin	Santa Cruz
52		Ross Creek Basin	Mendocino	146		Valencia Creek Basin	Santa Cruz
53		Gallaway Creek Basin	Mendocino	148		Elkhorn Slough Area	Monterey
54		Schooner Gulch Basin	Mendocino	153		Little Sur River Basin	Monterey
55		Gualala River Basin	Mendocino	155		Sycamore Canyon Basin	Monterey
56		Russian Gulch Basin	Sonoma	156		San Carpoforo Basin	San Luis Obispo
58		Scotty Creek Basin	Sonoma	159		Arroyo Laguna Basin	San Luis Obispo
59		Salmon Creek Valley Basin	Sonoma	164		Geronimo Basin	San Luis Obispo
61		Estero Americano Basin	Sonoma and Marin	169		Willow Creek Basin	San Luis Obispo
62		Estero de San Antonio Basin	Marin	179	3-14	San Antonio Creek Valley	Santa Barbara
63		Sand Point Area	Marin	181		Bear Creek Basin	Santa Barbara
66		Kehoe Creek Basin	Marin	182		Spring Canyon Basin	Santa Barbara
68		Drakes Bay Basin	Marin	183		Canada Honda Basin	Santa Barbara
69		Point Reyes Basin	Marin	184		Jalama Basin	Santa Barbara
71		Estero de Limantour Basin	Marin	186		Damsite Canyon Basin	Santa Barbara
72		Glenbrook Creek Basin	Marin	187		Canada del Cojo Basin	Santa Barbara
73		Muddy Hollow Basin	Marin	188		Gato Basin	Santa Barbara
75		Bear Valley Basin	Marin	190		Agujas Basin	Santa Barbara
78		Elk Valley Basin	Marin	191		Bulito Basin	Santa Barbara
80		Horseshoe Bay Basin	Marin	192		Canada de la Brea Basin	Santa Barbara
84		Marin Island Basin	Marin	193		Canada de Santa Anita Basin	Santa Barbara
91		Sulphur Springs Basin	Solano	194		Alegria Basin	Santa Barbara
95		Arroyo del Hambre Basin	Contra Costa	197		Canada San Onofre Basin	Santa Barbara
96		Little Bull Basin	Contra Costa	206		Eagle Canyon Basin	Santa Barbara
97		Big Bull Basin	Contra Costa	212		San Roque Basin	Santa Barbara
98		Crockett Basin	Contra Costa	214		Oriegas Basin	Santa Barbara
99		Canada del Cierbo Basin	Contra Costa	225		Escondido Canyon Basin	Los Angeles
100		Oleum Basin	Contra Costa	227		Corral Canyon Basin	Los Angeles
101		Rodeo Basin	Contra Costa	231		Santa Ynez Canyon Basin	Los Angeles
102		Refugio Basin	Contra Costa	232		Santa Monica Canyon Basin	Los Angeles
103		Pinole Basin	Contra Costa	252		La Jolla Basin	San Diego
103		Sobrante Basin	Contra Costa	257		South Las Chollas Basin	San Diego
106		Guadalupe Basin	San Mateo	258		La Paleta Basin	San Diego

* Numbers assigned to ground water basins identified in Appendix A and shown on Plate 4 of this report.
† Numbers assigned to ground water basins identified in Division of Water Resources publication, "Ground Water Basins in California, Water Quality Investigations, Report No. 3, 1952."

(2) The ground water has been developed in varying degree, as a source of water supply;

(3) Where water level data are available, a landward hydraulic gradient is indicated; however, information is not generally available as to direction of the hydraulic gradient in all of these areas;

(4) Chlorides in excess of 100 parts per million occur in the ground waters of localized areas within the coastal segment of the basin.

There are 71 ground water basins in which chlorides in the coastal segments exceed 100 parts per million (see Plate 4 and Table 1). For purposes of this report, a chloride content of 100 parts per million is arbitrarily considered as the criterion for saline degradation in the coastal segment of the ground water basin, since under natural conditions few if any coastal ground waters contain chlorides to that extent. It is believed that degradation in many of these basins is due to direct lateral movement of sea water. However, degradation could be due, at least in part, to other factors including:

(1) Direct infiltration of saline or brackish tidal waters through natural breaks in silt or clay layers, or through improperly constructed, defective, or abandoned wells;
(2) Upward or lateral movement of saline or brackish connate waters into fresh water-bearing deposits from adjacent and underlying older geologic formations;
(3) Interchange between aquifers, of waters of differing mineral quality through natural breaks in silt and clay layers, or through improperly constructed, defective, or abandoned wells;
(4) Downward movement of perched waters of poor quality;
(5) Percolation of water from highly mineralized springs, streams, or both;
(6) Downward seepage of industrial wastes and sewage;
(7) Adverse salt balance.

In general, most of the basins in this category are small, narrow, alluvium-filled valleys, in which there is now only limited development of ground water. Historical data pertaining to water quality, water level measurements, hydraulic gradients, and fluctuations of piezometric surfaces or of the free ground water table, are usually not available, other than field measurements and analyses made during the course of this investigation. A positive determination that sea-water intrusion is the cause of degradation of water quality in these coastal areas cannot be made until additional water level measurements and water quality data are obtained through continuing basic data collection programs.

There has been moderate to extensive development of ground water in a number of the basins identified in this category. Among these are:

(1) Mad River Valley in Humboldt County;
(2) Eel River Valley in Humboldt County;
(3) Suisun-Fairfield Valley in Solano County;
(4) Lompoc Plain in Santa Barbara County;
(5) Goleta Basin in Santa Barbara County;
(6) Carpinteria Basin in Santa Barbara County; and,
(7) Tia Juana Basin in San Diego County.

Draft on ground water supplies in these basins is generally fairly extensive in comparison to the resources of the basin. In some instances ground water levels in the coastal areas have been below sea level for varying periods of time, and a landward hydraulic gradient exists at least during the heavy pumping season. Unfortunately, the available long time hydrologic and water quality data for most of these basins are not adequate to positively identify sea water as the source of observed ground water quality degradation. Because of the importance of these basins, a continuing program of measurement of water levels, determination of hydraulic gradients, and analysis of ground waters should be conducted. Detailed geologic, hydrologic, and water quality studies should be undertaken immediately to positively establish the causes of ground water quality degradation. Only after the causes have been delineated can plans for prevention and control be formulated and put into effect, including the provision of supplemental water supplies where necessary.

AREAS OF NO APPARENT SEA-WATER INTRUSION

There is no reason to believe that ground water basins in which the following conditions now prevail are presently affected by sea-water intrusion, even though the water-bearing deposits at the coast line apparently extend below sea level and are open to the ocean:

(1) Development of the ground water for beneficial use has so far been moderate in comparison with the resources available;
(2) Where adequate information is available, a generally prevailing seaward hydraulic gradient is indicated. However, information is generally insufficient to determine position of the ground water surface or direction of hydraulic gradient;
(3) From the limited information available, there is no present evidence of high chlorides in the ground waters of the coastal segments of the basins.

There are 48 ground water basins in this category (see Table 1). In general, the great percentage of these basins are small, narrow, alluvium-filled valleys in which there has been only limited development of ground water. In these areas, also, there is limited historical data on water quality and hydrology except such as could be obtained during this investigation.

There are 5 basins of the 48 identified in this category which are important sources of water supply, and in which there is moderate development of ground water, namely:

(1) Smith River Plain in Del Norte County
(2) Carmel Valley in Monterey County
(3) Arroyo Grande Basin in San Luis Obispo County

(4) Santa Maria River Valley in San Luis Obispo County
(5) Santa Barbara Basin in Santa Barbara County

Draft on ground water supplies in these basins does not now appear to be extensive in comparison with the resources of the basin. Water levels are generally above sea level in the coastal segment, and a seaward hydraulic gradient exists over the entire basin, except during short periods of time.

As far as can be determined, ground waters of these basins have not as yet been affected by intrusion of sea water. However, any appreciable increase in pumping in the coastal segment of these basins could induce sea-water intrusion by lowering water levels and reversing the existing seaward hydraulic gradient. To obviate the possibility of future widespread degradation, effective controls and safeguards should be instituted if ground water development reaches the point where sea-water intrusion is threatened. Hydrologic and geologic studies should be made to determine ground water safe yield and optimum pumping pattern. A ground water monitoring program should be established and maintained to continually observe water levels and check water quality. Long range studies of future water requirements should be conducted, so that plans for supplemental supplies could be formulated and facilities developed in time to meet all prospective demands.

AREAS WHERE THE STATUS OF SEA-WATER INTRUSION IS UNKNOWN

This category encompasses 134 ground water basins in which there is little or no development of ground water, and no information could be obtained during this investigation to determine geologic, hydrologic, or water quality conditions in coastal segments.

In each of these basins it may be assumed that, with little or no development, encroachment of sea water is restrained for the present due to ground water levels in the coastal area being at or above sea level. However, there is danger that sea-water intrusion would occur if ground water supplies were overdeveloped.

All of these basins are limited in extent. In most instances, particularly in northern California, they are located in remote reaches of the coast line and are not readily accessible. It is probable, however, that in the future many of these areas will develop, as the population of the State increases, and will eventually draw upon their ground water resources. Thus, ground water conditions in these basins should be continually observed and carefully evaluated at the appropriate time to determine the extent to which they can be safely developed.

DESCRIPTIONS OF AREAS OF KNOWN SEA-WATER INTRUSION

There are presented herewith descriptions of the areas of known sea-water intrusion, including details of geologic, hydrologic, and water quality aspects.

Petaluma Valley

Petaluma Valley is the westernmost of a series of valleys adjacent to San Pablo Bay at the north end of San Francisco Bay, in Sonoma and Marin Counties. The valley extends north from San Pablo Bay a distance of about 16 miles, and occupies an area of about 45 square miles. About 10 square miles of the bayward portion is unreclaimed tidal marshland which is at or below sea level. Reclaimed portions of the tidal marshland are utilized for pasture and dry farming. The inland portion of the valley, north of Petaluma, is a rural area devoted largely to the poultry and dairying industries. This area is shown on Plate 5.

Surface and ground waters are used for a variety of purposes including domestic, irrigation, industrial, and stock-watering. Ground water is used to supplement the surface water supply for the City of Petaluma, which in 1951 obtained almost half of its supply from ground water. In years of deficient rainfall and runoff, ground water becomes the principal source of supply for Petaluma Valley. In 1949, an estimated 1,800 acre-feet of water were pumped for all uses. Of this total, approximately 760 acre-feet were for public supply, 250 acre-feet for irrigation, and the remainder for various domestic and industrial needs.[1]

Occurrence and Movement of Ground Water. Petaluma Valley is an alluvium-filled, structurally controlled depression, similar to Napa and Sonoma Valleys to the east. The valley floor is underlain by a thick series of water-bearing sediments including alluvium, the Merced and Petaluma formations, and volcanic rocks known as the Sonoma volcanics. Nonwater-bearing basement rocks underlie the central portion of the basin at depths ranging from about 800 feet to well over 2,000 feet. The principal sources of ground water are the alluvium and the Merced formation, which are described in more detail herein.

Alluvium of Quaternary age is divided into younger and older alluvium. The younger alluvium is made up chiefly of fine-grained silt, sandy clay, and thin gravel beds, with silts and clays predominating near the bay. Its thickness has not been definitely ascertained, but is believed to range from about 200 feet in the upper portion of the valley to as much as 300 feet in the bayward portion. There are no continuous confining beds which would impede the downward movement of waters from the surface. In general, permeability is low and yields to wells are small to moderate. Older alluvium underlying the younger alluvium in the valley floor is a somewhat more permeable unit, consisting of sand and gravel, and interbedded silt and silty clay. Its thickness is not definitely known but may approximate 200 feet. These alluvial deposits probably extend out beneath San Pablo Bay. It seems likely, however, that these water-bearing deposits are capped by relatively impermeable bay muds and thus not in direct hydraulic continuity with bay waters.

The Merced formation underlies the older alluvium beneath most of the valley floor and is exposed in the hills northwest of Petaluma. This formation is a marine deposit of Pliocene and Pleistocene age, consisting of massive beds of fine sand and sandstone with interbeds of clay, silty clay, and lenses of gravel. It is the principal source of ground water in the upland area northwest of Petaluma, and is tapped by deeper wells near the center of the valley and near the bay. Available information indicates that this formation may extend beneath the bay below the alluvium.

Ground water in both the younger and older alluvium north of Petaluma is generally unconfined, except in the bayward portion where confinement occurs in the older alluvium and to a lesser extent in the younger alluvium. In the Merced formation, water is known to be confined in the northern part of the valley where several wells flow in the spring. Near the bay, water in this formation may be confined by materials of low permeability in the overlying alluvium.

The Tolay fault passes through the northeastern portion of the basin. It is not known to cut deposits younger than the Merced formation, and therefore appears to have no effect on movement of ground water in the alluvium. No information is available to determine whether this fault may form an effective barrier to movement of ground water in the Merced formation.

Ground water in the area north of Petaluma is recharged largely by deep infiltration of rainfall and runoff. Ground water moves generally toward Petaluma Creek and thence downstream, discharging to both Petaluma Creek and into the tidal sloughs. In the tidal flats south of Petaluma, however, the fresh ground water body appears to be partially confined and overlain by lenses of brackish and saline water.

In recent years, overdevelopment of ground water supplies in the vicinity of Petaluma has caused localized overdraft conditions, but it does not appear that this overdraft problem is basin-wide as yet.

Quality of Water. Surface waters of Petaluma Valley above the area of tidal influence are of good mineral quality. Analyses of water in Petaluma Creek at Petaluma indicate that it is calcium bicarbonate in character, with a concentration of 390 ppm total solids, 80 ppm chlorides, and 0.16 ppm boron. Brackish to salty waters occur in the tidal reach of Petaluma Creek between the City of Petaluma and the bay. Water in Adobe Creek, two miles east of Petaluma, is calcium bicarbonate in character, containing 187 ppm total solids, 14 ppm chlorides, and no boron. Water in San Antonio Creek, three miles south of Petaluma, is magnesium bicarbonate in character, with a total solids content of 177 ppm, 26 ppm chlorides, and 0.07 ppm boron.

Ground water in the unconsolidated alluvium in the upper portion of the valley ranges from calcium-magnesium bicarbonate to sodium bicarbonate in character, with total solids ranging from 200 to 500 ppm and chlorides from 20 to 60 ppm. Analysis of water from a well in the vicinity of Petaluma, where intrusion of brackish water has occurred, indicates that in 1954 the degraded ground water there had a total solids concentration of as much as 885 ppm, and a chloride concentration of 362 ppm. Another well, approximately one mile to the east in an area unaffected by intrusion of brackish water, had a total solids concentration of 423 ppm and chloride concentration of 47 ppm. In the southern portion of the valley, in the area of tidal influence, ground water near Petaluma Creek and tidal sloughs is commonly brackish. Analyses of samples from two wells in this area in 1954 indicated total solids concentrations of 772 and 1,700 ppm, and chlorides of 146 and 835 ppm. Representative analyses of surface and ground waters are presented in Appendix A.

Status of Sea-Water Intrusion. Little data are available to determine when degradation of ground waters by intrusion of brackish bay water first began in the vicinity of Petaluma. Since 1850, when settlement of the area started, development of ground water has progressed slowly. The major development has occurred since 1945 and it is possible that deterioration of water quality due to sea-water intrusion began then or was rapidly accelerated at that time.

Since 1945, intensive ground water pumpage in summer months has been concentrated in an area east and northeast of Petaluma, which is only slightly above sea level. This heavy draft has caused water levels to be seasonally lowered below sea level, thereby inducing downward and lateral movement of brackish tidal waters into the pumping depression. The seasonal lowering of ground water levels below sea level is illustrated by the well hydrograph shown on Plate 6. During the winter months when pumpage is reduced, the depression disappears and a partial flushing by fresh water takes place. Despite this flushing action, quality of ground waters in this area of the valley has been progressively deteriorating. The chloride concentration of a well located 0.7 mile north of Petaluma Creek in the vicinity of Petaluma increased from 216 ppm in August, 1950, to 325 ppm in February, 1954. As of the summer of 1954, an area of approximately $\frac{3}{4}$ square miles was underlain by degraded water, as shown on Plate 5. In the fall of 1954, ground water levels in an area of approximately two square miles were below sea level.

In the tidal flat area, from Petaluma south to San Pablo Bay, there are few wells and little ground water pumpage. Little is known concerning the extent of ground water degradation. However, a large portion of this area is underlain by poor quality brackish water, particularly near the bay, Petaluma Creek, and the tidal sloughs. With the exception of areas adjacent to the hills, ground water is at or below sea level during the summer and fall months. Therefore, ground waters at shallow depths in the younger alluvium are subject to degradation by seepage of tidal waters into pumping depressions surrounding shallow wells. Analyses of samples from some shallow wells show chlorides in excess of 1,000 ppm. There are indications that ground water from depths of several hundred feet or more in the alluvium or Merced formation may have lower chloride concentrations than the shallow waters, but still in excess of 100 ppm.[1] However, extraction of water from these deeper zones is very limited.

It appears that sea-water intrusion in Petaluma Valley is not occurring directly from the bay by subsurface inflow, but rather through the downward and lateral movement of surface and near-surface brackish and saline waters.

Napa-Sanama Valley

Napa-Sonoma Valley, shown on Plate 5, consists of two parallel, elongated valleys in Napa and Sonoma Counties, the bayward portions of which are merged at San Pablo Bay. Sonoma Valley, the westernmost unit, extends northward from the bay a distance of 15 miles and occupies an area of approximately 35 square miles. Napa Valley extends northward from the bay a distance of 40 miles and occupies an area of approximately 85 square miles.

The merged bayward portion of these valleys is largely undeveloped tidal marshland, but some areas have been reclaimed and are utilized for pasture and dry farming. The inland portions of both valleys are developed by small diversified farms devoted to the raising of grapes, orchard crops, pasture, dairying and poultry. Numerous wineries are scattered throughout both valleys. The principal population centers are Napa, St. Helena, and Calistoga in Napa Valley, and Sonoma in Sonoma Valley.

Ground water is the principal source of water supply in Sonoma Valley. In Napa Valley, ground water is an important source of supply, but surface water is being increasingly utilized by towns and ranches, since the supply from wells in parts of the valley is not adequate to meet the increasing demand. Napa, St. Helena, and numerous ranches now obtain water from Lake Hennessy, a reservoir impounded behind Conn Dam on Conn Creek. Estimated ground water pumpage for the year ending March 31, 1950, was approximately 8,000 acre-feet, of which about 5,500 acre-feet were pumped in Napa Valley and 2,500 acre-feet in Sonoma Valley.[2]

Occurrence and Movement of Ground Water. Napa-Sonoma Valley is a structurally controlled depression underlain by water-bearing alluvial deposits of Recent and Pleistocene age, and by Sonoma volcanics of Pliocene age. The alluvial deposits include the younger alluvium of Recent age, the older alluvium and the Huichica formation of Pleistocene age, and the Glen Ellen formation of Plio-Pleistocene age. The principal sources of ground water are the younger and older alluvium.

The younger alluvium is mainly silt and clay with discontinuous lenses of sand and gravel. These deposits underlie the flood plains of Napa River and Sonoma Creek and the tidal marsh lands adjacent to the bay. Throughout a large part of the area, the younger alluvium is only a thin veneer covering the older alluvium. The older alluvium is composed of lenticular deposits of unconsolidated silt, clay, sand, and gravel; and there are no continuous impermeable beds which would restrict the downward movement of water from the surface. The older alluvium generally overlies the Huichica and/or the Glen Ellen formations and underlies the younger alluvium. The older alluvium probably exceeds 300 feet in thickness near the bay and extends beneath the bay for an unknown distance, where it is overlain by relatively impervious bay muds.

The Huichica and Glen Ellen formations occur beneath the older alluvium. These two formations consist chiefly of poorly sorted mixtures of silt and clay with lenses of sand and gravel. Permeability of both formations is low, and consequently yields to wells are often insufficient even for domestic needs. These formations may also extend beneath the bay under the alluvium.

The Sonoma volcanics generally underlie the Huichica and Glen Ellen formations beneath Napa-Sonoma Valley and are exposed in the adjacent hills. The Sonoma volcanics consist of a thick and highly variable series of volcanic rocks including basalt, andesite, rhyolite, tuffs and pumice. Small to moderate and locally large yields can generally be obtained from the tuffs and pumice, but the andesite and basalt flows are generally impermeable.

Ground water in the younger alluvium and in most of the older alluvium is unconfined; however, there are some localized areas of confinement in the older alluvium. Water in the Huichica and Glen Ellen formations is partially confined, and silt and clay in these formations confines water locally in the underlying Sonoma volcanics.

Ground water in the unconfined water body in the younger and older alluvium is replenished by infiltration of rainfall and seepage from streams. The source of water in the Huichica and Glen Ellen formations and the Sonoma volcanics is from infiltration of rainfall and stream seepage in the outcrop areas in the adjacent hills, and by downward seepage of water from the overlying alluvium where confinement is not complete and the pressure head is low. Under natural conditions, ground water moves in a bayward direction and discharges into the tidal marshlands and into Napa and Sonoma Rivers. Deep waters in the confined zones may discharge directly into San Pablo Bay further south.

Although overpumping of ground waters in the vicinity of Schellville in Sonoma Valley and between the City of Napa and Suscol Creek in Napa Valley has caused local overdraft, it does not appear that there is a basin-wide overdraft problem.

Quality of Water. Surface waters of Napa-Sonoma Valley above the area of tidal influence are generally of good mineral quality. Water from Schell Creek in Sonoma Valley is calcium bicarbonate in character with a concentration of 143 ppm total solids, 16 ppm chlorides and 0.14 ppm boron. Water in Sonoma Creek in Sonoma Valley is magnesium bicarbonate in character, containing 142 ppm of total solids, 14 ppm chloride and zero boron. In Napa Valley, water in Suscol Creek just above the area of tidal influence is calcium bicarbonate in character, with 136 ppm total solids, 10 ppm chlorides and zero boron. Water from streams and sloughs within the area of tidal influence is brackish to saline in character, with chlorides ranging from 7,400 to 10,800 ppm.

Ground water in the alluvial deposits in the central and northern portion of the area is generally calcium bicarbonate in character, with low total solids, chloride and boron. Analyses of samples from several wells in this area indicates total solids ranging from 166 to 225 ppm, chloride from 9 to 16 ppm, and boron from 0.1 to 0.2 ppm. Ground waters from the Sonoma volcanics are often of poor quality, but still usable for irrigation and domestic purposes. In some limited areas, however, boron concentration is over 10 ppm, rendering those waters unfit for irrigation use. Chlorides are generally less than 40 ppm, except in very localized areas.

Ground water from shallow wells in the bayward portion is generally sodium chloride or sodium bicarbonate in character. Analyses of samples from several wells in this area indicate a range in chloride concentration from 100 to over 1,000 ppm. Representative analyses of surface and ground waters are presented in Appendix A.

Status of Sea-Water Intrusion. Little historic data are available to determine when degradation of ground waters in Napa-Sonoma Valley first began. Prior to 1930, wells belonging to the City of Napa, located near the south city limits, were abandoned and destroyed because the water became too brackish to use.[2] An area of degraded water also occurs in the vicinity of Schellville, but it is not known when degradation first occurred.

In the vicinity of Schellville and Napa, ground water levels in the younger and older alluvium have been seasonally lowered to or below sea level in several isolated areas which are only slightly above sea level (see Plate 6). These depressions are caused by pumping of ground water from the several aquifers.[2] This condition of depressed water levels has induced downward and lateral seepage of brackish waters from the sloughs and tidal reaches of Napa River and Sonoma Creek into the pumping depressions. During the winter and spring months, there is some recovery of water levels, brackish waters are partially flushed out, and chloride concentrations drop considerably. As of the summer of 1954, several isolated areas adjacent to the tidal portion of the Napa River and Sonoma Creek were underlain by brackish waters with chloride concentrations in excess of 1,000 ppm, as shown on Plate 5. Brackish waters are largely restricted in occurrence to the unconfined water body in the younger and older alluvium. The Sonoma volcanics, occurring at depths of 300 feet or more beneath the alluvium, is generally protected from the overlying brackish water by impervious materials. However, in the vicinity of Napa, there has been some movement of brackish water into the Sonoma volcanics through deep wells which are perforated in both the alluvium and the Sonoma volcanics, or through wells which are otherwise improperly constructed or defective.

A large portion of the tidal flat area is underlain by poor quality water. The younger alluvium and perhaps portions of the older alluvium were deposited in tidewater and, therefore, these brackish waters appear to be connates, at least in part. Fresh ground water, which occurs in the lower portions of the older alluvium, is subject to degradation by seepage of the upper brackish waters into pumping depressions. However, the extent to which this degradation may have occurred is not known. As of about 1950, many shallow wells yielded brackish water with chloride concentrations of as much as 1,000 ppm. Brackish water is apparently restricted to approximately the upper 100 feet of sediments, and deep wells draw better quality water from zones below 200 feet, which are probably confined or partially confined.

In general, sea-water intrusion in Napa-Sonoma Valley occurs through the downward and lateral movement of brackish surface and shallow ground waters and it appears that sea-water intrusion is not occurring directly from the bay by subsurface inflow.

Santa Clara Valley

Santa Clara Valley occupies the alluviated area adjacent to the southern portion of San Francisco Bay in Alameda, Santa Clara, and San Mateo Counties. The valley is generally bounded by the Santa Cruz

Mountains on the west and the Diablo range on the east, and extends southward to a drainage divide at Morgan Hill in Santa Clara County. The west bay area from Palo Alto to South San Francisco in San Mateo County, and the east bay area from San Leandro to Richmond, largely in Alameda County, are heavily populated urban and suburban regions with considerable industrial development. Ground water use and development in both these areas is extremely limited. Surface water from the Hetch Hetchy Aqueduct of the City of San Francisco supplies the entire west bay area except for a small amount of ground water pumpage by private individuals and industries. In the east bay, the metropolitan and industrial areas are supplied almost exclusively by surface water, of which the greatest portion is furnished from the East Bay Municipal Utility District's Mokelumne Aqueduct.

There is extensive ground water use and development in the area south of San Leandro in southern Alameda County and north of San Jose in northern Santa Clara County. This portion of the valley is devoted largely to irrigated and dry farming, and to a lesser extent to urban, suburban, and industrial development. The principal centers of population are the Cities of Hayward, San Leandro, San Lorenzo, San Jose, and Palo Alto. The bayward portion is composed of tidelands, much of which is being or already has been reclaimed for industrial sites. A large portion of the tideland area of southern Alameda County is devoted to evaporation ponds.

This study is confined largely to those portions of the valley in southern Alameda County and northern Santa Clara County that constitute the principal area of ground water development, and where, as a consequence, intrusion of sea water has occurred. This area is shown on Plate 7.

Occurrence and Movement of Ground Water. Water-bearing formations in the area include alluvial, tideland, and shallow marine deposits of Quaternary age, and the Santa Clara formation of Plio-Pleistocene age.[3,4] Lying beneath the Santa Clara formation are nonwater-bearing sediments and crystalline rocks of Tertiary and older ages.

Alluvium in the area consists of unconsolidated mixtures of sand, gravel, silt, and clay; and occurs as alluvial fans and cones, and flood plain deposits. The alluvial fan deposits inter-finger with the tideland and flood plain deposits, and extend beneath the bay where they are overlain by bay mud. Three prominent alluvial cones, located on San Lorenzo, San Leandro, and Alameda Creeks, have been formed at the apexes of the alluvial fans. These cones, composed of sand and gravel, represent the coarse phases of the fan deposits.

The Santa Clara formation is exposed in the foothill areas to the east and west of San Jose, and extends beneath the Quaternary alluvium on the valley floor. This formation is similar in composition to the alluvium, but the sediments are more consolidated.

Ground water in the area occurs principally in an upper aquifer and a series of lower aquifers, as shown on Plate 8. The aquifers consist of a series of permeable sand and gravel beds which occur in both the alluvium and the Santa Clara formation. The upper aquifer is separated from the lower aquifers by extensive clay beds of low permeability. These aquifers merge in the areas adjacent to the foothills on the east and west sides of San Francisco Bay and in the area south of San Jose, forming the forebay.

The upper aquifer occurs within the upper 100 to 150 feet of sediments.[3] It is generally overlain by silts, clays, and bay muds in the bayward portions of the valley floor and beneath the bay. Under natural conditions, ground water in the bayward portions of the upper aquifer was under artesian pressure; but in much of the area water levels have been lowered below the upper confining layers, and in effect a free ground water table now exists.

The top of the series of lower aquifers occurs at 120 to 250 feet beneath the surface. Ground water in the lower aquifers is confined. As of 1953, although water levels were drawn below sea level, the lower confined aquifers supplied the bulk of ground water to the area.

Both the upper and lower aquifers extend beneath the bay. The upper aquifer is exposed to saline bay waters and has been extensively affected by sea-water intrusion. The lower aquifers, however, are generally well protected by several confining clay layers; and as yet no direct inflow of sea water from the bay has been detected.

These aquifers are recharged by subsurface inflow from the forebay area adjoining the foothills and extending south of San Jose. Infiltration of rainfall, stream flow, drainage from adjacent hills, and the unconsumed portion of water applied for irrigation are the principal sources of natural ground water replenishment to the forebay area. Ground water is also replenished by artificial means through the activities of the Santa Clara Valley Water Conservation District and the Alameda County Water District. As of 1957, the Santa Clara Valley Water Conservation District operated 21 artificial recharge projects located along streams south of San Jose; and the Alameda County Water District operated 3 projects in the Niles cone area adjacent to Alameda Creek.

Lateral migration of ground water is impeded by the Hayward fault.[3] This fault extends along the foothills of the Diablo Range except where it crosses the Niles cone between Niles and Irvington, (Plate 7). In 1950, ground water levels in the Niles cone averaged about 30 feet higher on the east side of the fault than on the west side. It is unlikely that sea water could intrude beyond this barrier. South of the Niles cone, where the Santa Clara formation outcrops at the base of the Diablo Range, the fault probably restricts lateral movement of ground water from the Santa Clara formation into the valley alluvium. The Mission fault is located about one mile east of the Hayward fault on the Niles cone, but is not considered an effective barrier to ground water movement. Coyote Hills also forms a partial barrier to the movement of ground water along the east side of the bay.

Prior to 1916, artesian conditions existed throughout much of the area[5,6]; but in subsequent years there has been a steady decline in water levels. Hydrographs of wells presented on Plate 9 show the downward trend of water levels since the 1920's. All hydrographs for wells in the area show a temporary raising of levels between 1937 and 1945 due to a period of above-normal precipitation; however, levels again declined after 1945 until 1950, when the lowest of all levels were recorded. Since 1950 there has been a slight rise in the average water levels, due in part to another period of above-normal precipitation.

The natural gradient for ground water in Santa Clara Valley is from the direction of the mountains or higher portions of the valley toward the bay. However, landward gradients have been established in the upper aquifer since the 1920's or before, resulting in subsurface inflow from the bay through breaks in the upper confining beds. This has resulted in intrusion of saline water throughout bayward portions of the upper aquifer, and has caused virtual cessation of ground water pumpage therein. Heavy pumping draft has in recent years caused the formation of pumping troughs in the lower confined aquifers, resulting in a landward hydraulic gradient and subsurface inflow of fresh ground water from beneath San Francisco Bay. The confining clays capping the lower aquifers and extending beneath the bay apparently are continuous and are sufficiently impermeable that waters in these aquifers have not as yet been degraded by direct intrusion of saline water. Subsurface inflow to the area from sediments beneath the bay has been estimated at about 25,000 acre-feet per year, for the period 1947-48 through 1951-52.[3,4]

In 1953, several pumping troughs were formed in the lower aquifers, as shown on Plate 7. The axis of one trough was located about 4 miles inland from the bay and extended about 10 miles westward from the Santa Clara-Alameda County line. The axis of another trough passed through Palo Alto and could be traced for a distance of about 5 miles. These two troughs are probably connected during certain periods of the pumping season. In southern Alameda County, a pumping trough existed in 1953 which extended from San Leandro Creek about 21 miles to the south. The axis of that trough roughly paralleled the bay shore and extended a maximum of 3½ miles inland near Hayward.

Quality of Water. Surface inflow into the area is generally of good mineral quality. Water from streams emanating from the Santa Cruz Mountains on the west side of the valley generally contains higher concentrations of total dissolved solids than that from the Diablo Range on the east side. Total dissolved solids concentration of surface water in the area is generally less than 500 ppm while chloride concentration averages less than 100 ppm.[3,4] Representative analyses of waters from Coyote, Stevens, Belmont, Alameda and San Leandro Creeks are presented in Appendix A.

Ground water is generally of good mineral quality where unaffected by sea-water intrusion, although there are local areas of poor quality water along fault zones. Analyses of samples from wells in the upper aquifer and in the forebay area indicate that concentrations of total dissolved solids range from about 225 to 850 ppm, chlorides from 11 to 150 ppm, and boron ranges from zero to 5 ppm. Mineral quality of water in the lower aquifers is similar to that of the upper aquifer. Concentrations of total dissolved solids range from about 300 to 1,000 ppm, chlorides vary from 23 to 100 ppm, and boron ranges from zero to 1 ppm. Since the 1920's, numerous wells extracting water from the upper aquifer and portions of the lower aquifers have shown a steady increase of chloride concentration to over 1,000 ppm, indicating the effect of sea-water intrusion. Changes in chloride concentration for various years are shown graphically on Plate 9. Appendix A presents representative mineral analyses of ground waters in Santa Clara Valley.

Status of Sea-Water Intrusion. Salt-water invasion of the upper aquifer was recognized as early as 1920 in wells located near the bay, in the areas east of Palo Alto and west of Centerville. By 1925, steadily increasing irrigation drafts had resulted in lowering of ground water levels far below sea level. This condition of depressed water levels induced saline intrusion into the upper aquifer and forced abandonment of many irrigation wells. Indications are that sea water may have seeped into the upper aquifer near the bay through natural breaks in the overlying clay layers, through abandoned wells, or through openings in the surface clay and mud created by earlier dredging operations near the shore. By 1928, the situation had become so serious that a line of abandoned wells, which had been dug in 1904 within the tidelands of the bay near Palo Alto, were filled and sealed.[8] The wells had been left uncapped, and the casings had rusted and become defective; consequently, saline water from the bay was entering aquifers through these wells.

Intrusion into the upper aquifer has progressed inland at a rate varying with the ground water draft and recharge from surface streams. In 1939, a survey of saline ground water conditions was conducted by

Poland and Tolman.[8] It was found that salt-water encroachment into the upper aquifer had reached a maximum of 1½ miles inland from the bay near Palo Alto and Moffett Field. During a water quality sampling program conducted in 1949-50,[3] 27 wells used in the 1939 study were resampled. It was found that there had been no appreciable change in the chloride content in the water from these wells between 1939 and 1949. Therefore, it appears that in the Palo Alto area, there has been little or no change in the status of sea-water intrusion in the upper aquifer since 1939. However, in the Centerville area, salt water has been gradually advancing inland. In 1926, the 300 ppm isochlor was about three miles inland, and in 1953 was as much as eight miles inland. Since 1939 there has been almost a complete abandonment of shallow wells in the bayward portion of the valley. Extent of sea-water intrusion in the upper aquifer is shown on Plate 7.

In addition to the salt-water invasion of the upper aquifer, increased chloride concentrations have been noted in some waters from the lower aquifers. By 1951, saline water with chloride concentration in excess of 350 ppm was being pumped from the lower zones in an area of approximately 600 acres. At least seven deep wells were affected at that time.[3] In 1956, ground waters in the lower aquifers in an area of over 2,800 acres contained chlorides in excess of 350 ppm. Degradation of ground water in the lower aquifers has apparently been caused by downward movement of saline ground water from the upper aquifer either by spilling over the edge of the separating clay bed, through natural breaks or imperfections in the clay layers, through defective well casings which penetrate both zones, by means of wells which are perforated in both zones, improperly constructed or abandoned wells, or by a combination of such means.

Sea-water intrusion near Palo Alto at the present time appears to be of a less serious nature than in the vicinity of Centerville. As shown on Plate 8, the salt-water interface in the upper aquifer is as yet a long distance from the edge of the clays which overlie the lower aquifer in the Palo Alto area. In the Centerville area, however, salt water in the upper aquifer has advanced close to the edge of the confining clays.

At present, indications are that subsurface inflow from the direction of the bay to the lower water producing zones is of good mineral quality. The volume of fresh water actually stored beneath the bay and the location of the interface between the fresh water and saline water are not known. However, in view of the present overdraft and the prospects of increased future overdraft unless supplemental water becomes available, it is probable that fresh waters stored in the confined aquifers beneath the bay ultimately will be depleted. Fresh water withdrawn from storage from beneath the bay constitutes "mining" of ground water and cannot be considered a firm supply.[3] However, as long as there is fresh water in the aquifer beneath the bay, it will act as a buffer and retard the landward intrusion of saline water into the lower confined zones.

The Department of Water Resources was directed by the Legislature to investigate salt-water intrusion conditions in southern Alameda County. A two-year study was initiated in 1957 for the purpose of obtaining detailed information on causes and extent of intrusion. Wells which are suspected of allowing interchange of waters from the upper to the lower aquifers are being located, and the degree of degradation caused by each is being ascertained. As this study progresses, many of the faulty wells are being repaired or properly sealed. It is contemplated that, as a result of this study, corrective action will be taken at all wells shown to be causing pollution.

Pajaro Valley

Pajaro Valley comprises an area of approximately 75 square miles adjacent to the Pajaro River. The area, shown on Plate 10, extends from Elkhorn Slough on the south to the Santa Cruz Mountains on the north and east. The largest use of water in Pajaro Valley is for irrigation, with smaller demands for domestic and industrial needs. Ground water is the primary source for irrigation and industrial uses.

Occurrence and Movement of Ground Water. Ground water in the Pajaro Valley area is stored in relatively well defined aquifers in Tertiary and late Quaternary deposits. These water-bearing units include Quaternary valley fill, Pleistocene terrace deposits, the Aromas formation of Pleistocene age, and the underlying Purisima formation of Pliocene age. Underlying the Purisima formation are nonwater-bearing rocks, consisting of the Santa Lucia quartz diorite and related igneous rocks and sediments of the Monterey group.[9]

Ground water in the valley floor area occurs in three distinct zones, designated the shallow, intermediate, and deep zone.[10] These zones occur within the Quaternary deposits and are characterized by well-defined aquifers, composed primarily of sands with small gravel bodies of limited areal extent. These zones are separated by relatively extensive blue clay strata which greatly impede the downward movement of ground water. The majority of wells extract ground water from the intermediate zone.

The shallow zone extends from land surface to a depth of up to 100 feet (Section C-C′, Plate 11). Areas of unconfined semi-perched water are found throughout this zone, which is underlain by a relatively extensive blue clay aquiclude.

The intermediate zone lies below the shallow zone, and extends to a depth of approximately 200 to 300 feet (Section C-C′, Plate 11). Ground water is largely confined, although there are discontinuities in the confining clay members. This zone is probably exposed on the ocean floor between two and five miles off the coast in the Monterey Submarine Canyon (Section C-C′, Plate 11).

The deep zone underlies the intermediate zone, and extends to a depth of approximately 800 feet below land surface. Ground water in this zone is also confined. The piezometric surface is higher than that of the intermediate zone; and several wells near the coast flow during the winter and early spring.

These three aquifers merge into a forebay in the area north, east, and south of the City of Watsonville. This area is underlain by permeable deposits and is the principal source of ground water replenishment to the intermediate and deep zones. However, there may be some contribution from the shallow zone, through leakage or discontinuities in the aquiclude, particularly in the area west of Aromas.

There are no known barriers to the lateral movement of ground water in Pajaro Valley. The Vergeles fault in the eastern portion of the valley, approximately seven miles from the coast line, apparently cuts all of the formations older than the terrace deposits, but does not obstruct the lateral movement of water.

The shallow zone is recharged by percolation from the Pajaro River and other surface runoff, rainfall, and return irrigation water. Movement of ground water in this zone is generally to tidal sloughs and the lower reaches of the Pajaro River; however, there is some percolation to the intermediate zone where breaks in the blue clay layer exist and where hydraulic conditions are favorable.

Under natural conditions, the general direction of ground water movement in the deeper zones was from the uplands to Monterey Bay. However, overdraft of the ground water in the intermediate zone has caused a pumping trough to develop immediately west of Watsonville. A landward gradient has thereby been created, and sea water has intruded into the intermediate zone.

The axis of the trough as of 1947 was located about one and one-half miles inland from the coast and about three miles southwest of Watsonville. It extended about two miles across the valley floor and was roughly parallel to the coast line (Plate 10). Water levels were below sea level in an area of approximately seven and one-half miles at that time. By the summer of 1957 the axis of the pumping trough had moved inland about one-half mile.

The overdraft in the confined zones was estimated at 3,700 acre-feet per year in 1948-49.

Quality of Water. Surface waters of the Pajaro Valley watershed are generally of good to excellent mineral quality, and are suitable for most irrigation uses. Analysis of a sample from the Pajaro River near Watsonville shows 19 ppm chloride, 1.2 ppm boron and 229 ppm total dissolved solids. Quality of Pajaro River water near its terminus varies greatly with the tide. Analyses obtained during periods of low tide, when there is seaward flow, indicate the water is of excellent mineral quality. However, during the periods of reversed flow, sea water enters the channel and affects quality of the water for a distance up to about two miles inland. A sample of such water obtained near the mouth of the river during a period of reversed flow contained nearly 11,900 ppm of chlorides and over 21,600 ppm of total dissolved solids. Analyses of Pajaro River waters are presented in Appendix A.

Ground waters are generally suitable for irrigation uses, except for semi-perched waters in the shallow zone, and in the intermediate zone along the coast where sea-water intrusion has occurred.

Semi-perched ground waters in the shallow zone are often of poor quality and vary greatly in mineral characteristics. These waters are not used except in isolated cases. Ground water in the intermediate zone is generally suitable for most irrigation uses. Where sea-water intrusion has not occurred, this water is calcium-magnesium bicarbonate in character with total dissolved solids ranging from 250 ppm to over 1,000 ppm and averaging less than 500 ppm. Chloride content averages less than 50 ppm. However, due to intrusion of sea water, ground water in this zone along the coastal section is sodium chloride in character. In 1949 the chloride concentration ranged from less than 100 ppm to over 1,300 ppm. Since 1949, several of the wells showing high chlorides have been abandoned, and the maximum chloride concentration found in 1955 was 620 ppm. Analyses of representative ground waters are presented in Appendix A, and changes in chloride concentration of ground water from a well near the coast are shown graphically on Plate 12.

Only limited data are available concerning the quality of ground water in the deep zone; however, the analyses indicate that the water is of excellent quality with low total dissolved solids concentration. There is no evidence of sea-water intrusion in this zone.

Status of Sea-Water Intrusion. Development of ground water in Pajaro Valley began in November, 1851, when farming was inaugurated in the valley by early settlers. In many wells on the valley floor, water rose to the surface under artesian pressure, at least during part of each year. These flowing wells were still quite numerous as late as 1940. Sea-water intrusion in the intermediate zone of Pajaro Valley was first reported in the early 1940's. Although factual data on ground water levels for the period immediately preceding this first recognized degradation are not available, it may be assumed that a pumping trough was present and that ground water levels were below sea level. The first detailed field studies took place in the summer of 1947. At this time, high chloride concentrations were noted in several wells along the coast and the water levels were found to be below sea level. Under such hydrologic conditions, the normal direction of movement of ground water was reversed, resulting in inflow of sea water from Monterey Bay, which in 1947 had advanced inland as much as one mile. As of the summer of 1952, the area degraded by intrusion of sea water was not significantly greater than in 1947.

The following trends in status of sea-water intrusion in Pajaro Valley were evident by the summer of 1957:

(1) During the past 10 years, the area affected by sea-water intrusion has increased;

(2) In most cases, the concentration of chlorides in wells affected by sea-water intrusion has increased;

(3) Some wells in the area affected by sea-water intrusion have been abandoned because of excessive chlorides.

Sea-water intrusion in Pajaro Valley is related to the quantity of water pumped from the intermediate zone and the rate of ground water recharge to the zone. During summer pumping periods, in years when replenishment is not sufficient to maintain water levels above sea level, pumping troughs develop and sea water advances inland, as shown by an increase in chloride concentrations in wells along the coast. In the winter and early spring when pumpage is reduced and recharge greatest, the pumping troughs are partially or completely eliminated, depending upon the amount of replenishment. As a result, a partial flushing action takes place and chloride concentrations in wells are reduced. The relationship between chloride concentrations and ground water level fluctuations is depicted graphically on Plate 12 for a typical well near the coast.

The Department of Water Resources is currently conducting an investigation of water quality problems in Pajaro Valley. The report on this investigation will summarize information on geology, water utilization, and water supply. It will evaluate water quality problems and influencing factors, and will present recommendations regarding steps which might be taken to alleviate these problems.

Salinas Valley Pressure Area

Salinas Valley is a narrow, elongated, northwest-southeast trending valley located largely in Monterey County. The valley, which is about 90 miles long and averages approximately 5.5 miles in width, extends between the Santa Lucia Range and the Sierra de Salinas on the southwest and the Gabilan Range on the northeast. The principal center of population is the City of Salinas which lies about 11 miles inland from Monterey Bay.

Lands in the valley are devoted primarily to the production of irrigated crops, with urban and industrial land uses of secondary importance. Irrigated crops include lettuce and artichokes, and lesser amounts of sugar beets, alfalfa, and grain. Ground water is the only source of supply for the valley. The seasonal irrigation water requirement for the valley has been estimated to be 261,800 acre-feet as of 1953.[11] This represents about 95 percent of the total water usage for that year.

Salinas Valley has been subdivided into the following hydrologic units: Pressure Area, East Side Area, Forebay Area, and Upper Valley Area. Sea-water intrusion has affected only the Pressure Area in the coastal segment of the valley; therefore, the following discussion will be restricted to that hydrologic unit, which extends from Monterey Bay approximately 15 miles inland. The area of investigation between Monterey Bay and the City of Salinas is shown on Plate 10.

Occurrence and Movement of Ground Water. Fresh-water-bearing sediments in Salinas Valley include Recent dune sands, Recent alluvium, older alluvium of Pleistocene age, and the Paso Robles formation of Plio-Pleistocene age. Nonwater-bearing sediments and crystalline rocks of Tertiary and older ages underlie the Paso Robles formation.

The principal aquifers in the Pressure Area are designated as the 180-foot and 400-foot aquifers because of their average depths below ground surface. It is suspected that there are water-bearing materials below the 400-foot aquifer, but their location, depth, and extent are unknown.

The 180-foot aquifer is overlain by a shallow perched ground water body of poor mineral quality. Water from this perched zone is not used in any significant quantity. The 180-foot aquifer is separated from the perched zone by a thick series of impermeable clays. The 400-foot aquifer is likewise separated from the 180-foot aquifer by thick impermeable clays as shown on Plate 11. These clay layers effectively confine the ground waters in the 180-foot and 400-foot aquifers of the Pressure Area and preclude their replenishment by direct percolation from rainfall and/or runoff on the surface of the area. Their supply is obtained by subsurface inflow from the Forebay Area south of Salinas. There are no known barriers to the lateral movement of ground water in Salinas Valley.

Offshore from Salinas Valley lies one of the largest submarine canyons in the world, known as the Monterey Submarine Canyon. It extends from near the shore line approximately 50 miles seaward to the base of the continental slope. The head of this canyon has cut into alluvium deposited by the Salinas River and adjacent streams. A survey of Monterey Bay bottom sediments[12] indicates the presence of mud, silt, sand and gravel. A gravelly outcrop located in the canyon walls is probably the seaward extension of the 180-foot aquifer (Plate 11). The aquifer is thus exposed to saline waters of Monterey Bay. Detailed bottom sampling surveys have not extended far enough seaward to indicate the location of the 400-foot aquifer outcrop, if any.

Ground water levels in Salinas Valley have shown a general steady decline in the past decade because of the extensive development of ground water for farming, domestic and metropolitan use. Ground water fluctuations at key wells in the Pressure Area are shown on Plate 12. These graphs indicate that ground water levels are progressively declining in both the 180-foot and 400-foot aquifers. Available data are not adequate to show the true distance inland that water levels were depressed below sea level in either the 180-foot or 400-foot aquifers in 1954. However, ground water contours of 10 and 20 feet below sea level for the 180-foot aquifer and 400-foot aquifer respectively are shown on Plate 10. Also shown for the 180-foot aquifer is the increase in area between 1931 and 1944 where water levels were below sea level.

The natural ground water gradient in Salinas Valley is from upper portions of the valley westward toward Monterey Bay. However, depression of water levels during heavy summer pumping periods has caused the formation of a pumping trough which results in a reversed hydraulic gradient and subsurface inflow from beneath Monterey Bay. In 1954 a trough was developed in the 180-foot aquifer which extended from near Moss Landing to a point about 18 miles inland (Plate 10). Unlike troughs developed in many coastal basins, the axis of the Salinas Valley trough trends inland from north to south. The development of the trough and the resulting reversed hydraulic gradient caused an estimated inflow of 12,000 acre-feet of water from the seaward side of the axis in 1945.[13] A trough probably develops each year in the 400-foot aquifer, but lack of water level information does not permit its exact delineation.

Quality of Water. Surface waters from the Santa Lucia Range to the southwest of the valley are of good mineral quality while those from the Diablo Range to the northeast have comparatively high concentrations of dissolved solids. About 70 per cent of the total runoff comes from the Santa Lucia Range. Analyses of Salinas River water taken during the winter of 1953 indicated that the water was calcium bicarbonate in character and contained 513 ppm dissolved solids, 61 ppm chlorides, and 0.40 ppm boron. An analysis of water from Gabilan Creek, which heads in the Diablo Range, showed the water to be sodium bicarbonate in character, with 605 ppm dissolved solids, 130 ppm chlorides, and 0.10 ppm boron. As waters in the Salinas River reach the area of tidal influence from Monterey Bay, the salinity increases rapidly.[13] Tembladera Slough near Monterey Bay contains saline water with a dissolved solids concentration of 996 ppm, 174 ppm chloride, and 186 ppm sodium. Analyses of these surface waters are tabulated in Appendix A.

Native ground water in the Pressure Area is generally of good mineral quality, commonly a calcium bicarbonate water containing less than 1,000 ppm total dissolved solids, less than 100 ppm chlorides and less than 0.20 ppm boron. Analysis of a typical ground water from the 180-foot aquifer near Salinas shows 310 ppm dissolved solids, 57 ppm chlorides, and 0.13 ppm boron.

Waters from numerous wells near the coast in the 180-foot aquifer have shown steady increases in chloride concentration over the past decade. Concentrations of chlorides from some wells in the 180-foot aquifer were in excess of 400 ppm as of 1954, indicating the effects of sea-water intrusion. Chloride concentrations in wells near the coast in the 400-foot aquifer have increased in recent years to over 200 ppm during periods when water levels were depressed below sea level (Plate 12 and Appendix A).

Status of Sea-Water Intrusion. Degradation of ground water quality along the coastal portion of Salinas Valley was noted prior to 1944. The first concerted effort to identify and determine the extent of degradation was made in 1945. At that time, the degraded zone involved only the 180-foot aquifer for a distance of about 1¾ miles inland from the bay shore, as shown on Plate 10. The rate of inland encroachment between 1944 and 1945 was on the order of 600 feet per year. By 1954 the degraded zone had extended another 4,000 feet inland. As sea-water intrusion in the 180-foot aquifer extended inland, wells were deepened or drilled into the 400-foot aquifer, which showed no evidence of intrusion as of 1945. However, chlorides in excess of 100 ppm in the 400-foot aquifer in the area adjacent to the coast were noted in 1954, and it is presumed that sea-water intrusion is now also occurring in this aquifer. As shown on Plate 10, intrusion in the 180-foot aquifer had reached a point about 2½ miles inland from the coast while intrusion in the 400-foot aquifer had reached at least two miles inland in 1954. Section D-D′, Plate 11, indicates graphically the intrusion in relation to the water-bearing sediments of the valley.

Sea-water intrusion in Salinas Valley is caused directly by continued overdraft, which has resulted in lowered water levels in the 180-foot aquifer and development of a pumping trough. This trough, which is developed in the summer months each year, creates a reversed hydraulic gradient from beneath the bay toward the axis of the trough. Since the outcrop of this aquifer on the bay floor is close to the shoreline, there is little time lag between formation of the pumping trough and intrusion of sea water. Similar conditions probably exist in the 400-foot aquifer, but little is known of the location or extent of the pumping trough.

Continued overdraft in the Salinas Valley Pressure Area will result in further degradation of the ground water. As stated previously, inflow to the 180-foot aquifer from beneath Monterey Bay was estimated as 12,000 acre-feet in 1945. As the axis of the pumping trough moved inland and deepened in subsequent years, this amount undoubtedly increased. This increase would have continued if it were not for the fact that pumpage has been gradually reduced in the 180-foot aquifer as the water became degraded beyond the point of usability. At the same time pumpage has been correspondingly increased in the 400-foot aquifer, but this probably affords only temporary relief. As can be seen on Plate 10, sea-water intrusion in the 400-foot aquifer as of 1954 has extended almost as far inland as that in the 180-foot aquifer; and this has happened in a much shorter time. Wells deepened to water-bearing materials that may exist below the 400-foot aquifer in the intruded zone might produce fresh water for a while. However, it is probable that these aquifers outcrop in the walls of Monterey Submarine Canyon; and a heavy draft of ground water would result in sea-water intrusion, as in the other aquifers.

Sea water is not the only source of degradation in the 180-foot aquifer. In the vicinity of Salinas, poor quality waters from the perched water body are apparently migrating downward through natural gaps in the underlying clays; or through breaks caused by defective, improperly constructed or abandoned wells. It is apparent that this type of degredation could also pose a threat to ground waters in the 400-foot aquifer.

Oxnard Plain Basin

The Oxnard Plain Basin is a portion of the Oxnard Plain located in the southern part of Ventura County. Land use is primarily agricultural; however, there are some industries, as well as a producing oil field, and two naval installations at Port Hueneme and Point Mugu. The larger centers of population within Oxnard Plain Basin are Oxnard and Port Hueneme, with populations of 28,897 and 8,750, respectively, as of 1957. Oxnard Plain Basin is shown on Plate 13.

Oxnard Plain Basin is hydraulically interconnected with the Oxnard Forebay and Pleasant Valley Basins, and to a limited extent with Mound Basin to the north and east. Although the other basins affect ground water in Oxnard Plain Basin, as discussed below, they are not in immediate jeopardy of sea-water intrusion.

Occurrence and Movement of Ground Water. The Oxnard Plain Basin contains three principal water-bearing zones, designated the Oxnard, Mugu, and Fox Canyon aquifers in order of their depths below ground surface. These aquifers are all confined in Oxnard Plain Basin. They are depicted on the geologic sections of Plate 14, which also show their seaward extensions as extrapolated from logs of wells. Of the three aquifers, the Oxnard is now the most highly developed. The Oxnard aquifer underlies all of the Oxnard Plain Basin and extends northeastward into the Oxnard Forebay where it is recharged by direct percolation from the surface. In Oxnard Plain Basin, however, the Oxnard aquifer, from 75 to 200 feet in thickness, is overlain by fine-grained, relatively impermeable sediments which range in thickness from a few feet to 150 feet. The Mugu aquifer underlies a portion of the Oxnard Plain Basin and continues eastward into Pleasant Valley Basin. The aquifer extends northeasterly into Oxnard Forebay Basin where it is folded upward and is recharged from the Oxnard aquifer. The Fox Canyon aquifer underlies much of Oxnard Plain and, like the Mugu aquifer, extends northeasterly and easterly. The Fox Canyon aquifer is replenished in part in the Oxnard Forebay, and also is supplied from surface outcrops further inland.

In Oxnard Plain Basin, most wells obtain water from the Oxnard aquifer, but many wells in the southern part of the basin and east of the basin obtain water from the Mugu aquifer. Because of its depth in Oxnard Plain Basin and the presence of the two shallower aquifers, only a few deep wells obtain water from the Fox Canyon aquifer. It is extensively utilized, however, in the area east of this basin.

Beneath the Oxnard Plain Basin, the aquifers are overlain by fine sediments of low permeability; and presumably this capping continues offshore. Two steep submarine canyons, one at Port Hueneme and a second at Point Mugu, expose the aquifers to the ocean relatively near the shore. At these points the seaward extensions of the aquifers are of minimum length, and consequently, wells near these areas are more vulnerable to sea-water intrusion. Outcrops of the aquifers on the walls of these canyons are shown diagrammatically on the geologic sections of Plate 14.

Under native conditions of surplus supply, ground water moved westerly and southwesterly beneath the Oxnard Plain Basin, discharging to the ocean through seaward extensions of the aquifers. Increased ground water extractions in recent years have resulted in reversal of ground water gradients. Direction of subsurface flow within all three aquifers has been landward since approximately 1947.

The elevation of the ground water surface in Oxnard Plain was accurately established in December, 1955. The extent of the area in which ground water levels were below sea level at that time is depicted on Plate 13. The lowest levels reached during the period of record, however, occurred in 1951. There has been some recovery since then, particularly in the Oxnard Forebay, due probably to increased precipitation and further development of surface supplies. In the coastal portion of the Oxnard Plain Basin, the degree of recovery has been small, and levels are still below sea level.

Quality of Water. Surface waters of the Santa Clara River are of good mineral quality during periods of flood runoff. These waters are predominantly calcium sufate or calcium-sodium sulfate in character and total dissolved solids range from 400 to 1,000 ppm. Chlorides are generally less than 50 ppm and boron less than 0.5 ppm. During periods of low flow, mineral concentrations are considerably higher.

In the Oxnard Plain Basin, ground waters of the Oxnard and Mugu aquifers, when unaffected by sea-water intrusion, are predominantly calcium sulfate in character. These waters range from Class 2 to Class 3 for irrigation use and are generally suitable for domestic use, although they are very hard. The total dissolved solids content ranges from 640 to 1,450 ppm and boron from 0.2 to 0.9 ppm. Ground water in the Fox Canyon aquifer is essentially the same except that sodium occasionally predominates. Representative analyses of surface and ground waters are listed in Appendix A.

Status of Sea-Water Intrusion. Increases in ground water salinity due to sea-water intrusion into the Oxnard aquifer at Port Hueneme and the Mugu and Oxnard aquifers near Point Mugu became apparent in 1951. Since that time, ground water salinity has continued to rise in both these areas. By December, 1955, in the vicinity of Port Hueneme, ground water containing in excess of 100 ppm of chlorides had advanced inland about 0.7 mile. The advance at Point Mugu has not been as accurately determined because of the absence of water wells in this area. Areas presently affected by sea-water intrusion are approximately delineated on Plate 13.

The progressive decrease in ground water levels and attendant increase in chloride concentration for key wells at Port Hueneme and Point Mugu are shown graphically on Plate 15. The graphs for wells 1N/21W-30F1 and 1N/21W-31L1, which are located about three and two miles, respectively, inland at Point Mugu, indicate that a landward ground water slope existed as early as 1947; and show a progressive increase in slope since that date. These observations indicate sea-water intrusion to be accelerating in this area. The chloride ion concentration at well 1S/21W-5H1 is shown to have risen from less than 100 ppm in 1949 to 13,200 ppm in 1955.

The graphs for well 1N/22W-20R1 located near the coast at Port Hueneme indicate that since 1948 ground water levels have been depressed below sea level in summer months but have risen to sea level or above in the winter. The periods in which levels have been below sea level, however, have become progressively longer. Since October, 1950, the chloride ion concentration has increased rapidly, from less than 50 ppm to a high of 3,100 ppm by September, 1954. These observations suggest a seasonal reversal in the direction of ground water movement with landward movement predominating. Since 1952, the average slope of the ground water surface shows little change in magnitude, suggesting that although sea water is intermittently advancing into the basin at Port Hueneme, there has been no appreciable acceleration in rate of advance of intrusion since that date.

West Coast Basin

The West Coast Basin encompasses an area of approximately 158 square miles in the western portion of the Los Angeles Coastal Plain in Los Angeles County. It extends westerly from the Newport-Inglewood uplift, a prominent northwest-trending structure formed by a series of en-echelon faults and folds, to the Pacific Ocean; and is bounded by the Ballona Escarpment on the north and the Los Angeles-Orange County line on the south. Structural and other geologic features of the area are illustrated on Plate 16.

Initially, the principal extractions of ground water in West Coast Basin were for domestic and agricultural purposes. During the past thirty years of rapid development, the area has been transformed from an agricultural to an industrial economy. As a result, extractions for agricultural purposes steadily declined and municipal and industrial utilization increased. Expanding urban and industrial demands have increased ground water extractions from approximately 10,000 acre-feet in 1904 to more than 90,000 in 1953. These excessive ground water withdrawals and decreasing water levels necessitated the importation of water from the Owens Aqueduct System in 1935, and subsequently Colorado River water in 1949. During the fiscal year 1953-54, extractions decreased slightly due to increased importations and by 1956-57, withdrawals were reduced to approximately 70,000 acre-feet as a result of voluntary curtailment by major producers from the basin. Despite the importation of water from remote areas and curtailment of extractions, the water supply problems remain critical.

Occurrence and Movement of Ground Water. The principal water-bearing deposits in the West Coast Basin were laid down during the Pleistocene and Recent epochs. They occur in rather distinct sand and gravel layers, separated by clay and silt lenses of variable thicknesses. Ground water in aquifers in most of the area is confined by the clay and silts. In general, these sediments range in thickness from a few feet to approximately 1,200 feet and extend northward from Palos Verdes Hills to the Santa Monica Mountains, and eastward across the Newport-Inglewood uplift into the Central Coastal Plain. They also extend seaward for some distance beneath the continental shelf in Santa Monica and San Pedro Bays.

Underlying these Quaternary deposits are essentially nonwater-bearing Tertiary sediments which range in thickness from 4,800 feet in the northern part of the basin to over 14,000 feet in the Long Beach area. Water-bearing deposits are illustrated stratigraphically by geologic sections on Plate 17.

The more important deposits of Recent age are those of fluvial origin that were deposited in rather narrow channels excavated by ancestral Los Angeles and San Gabriel Rivers. These backfilled erosional features are referred to as Dominguez gap, which extends southward between Dominguez Hill and Cherry Hill, and Alamitos gap, which extends southwesterly from Bixby Hill beyond the basin to Landing Hill in Orange County. The water-bearing deposit of Recent age in Dominguez gap, desigated the Gaspur zone, slopes southward toward San Pedro Bay where its base is 150 feet below sea level. In general, this aquifer is characterized by clean, coarse sand and gravel overlain by silty and sandy clay. A similar deposit is present in Alamitos gap but has not formed a well-defined aquifer. This deposit is significant, however, since it extends inland from the coast across the Newport-Inglewood uplift, and may permit landward movement of sea water.

Upper Pleistocene deposits underlie all of the West Coast Basin and form the surface materials over much of the area. In downward succession, they consist of a thin capping terrace deposit, a thin layer of Palos Verdes sand, and a thick section of unnamed deposits. These unnamed deposits consist of fine-grained sediments containing semi-perched ground water and coarse water-bearing basal sections identified as the "200-foot sand" and the Gardena water-bearing zone. The "200-foot sand" underlies an area of approximately 84 square miles. It is an aquifer of moderate to low permeability characterized largely by sand with variable amounts of gravel, sandy silt, and clay. Thickness of the "200-foot sand" is quite variable, but in general, it thickens inland from coastal regions. The Gardena water-bearing zone is composed of coarse fluvial materials deposited in a shallow channel cut by an ancestral Los Angeles or San Gabriel River through the upper Pleistocene deposits and the "200-foot sand." It underlies an area of approximately 20 square miles, extending eastward from Redondo Beach to the City of Gardena and across the crest of the Newport-Inglewood uplift into the Central Coastal Plain.

Lower Pleistocene deposits contain the principal aquifers in the area and include the Silverado water-bearing zone and the "400-foot gravel" in the San Pedro formation. The San Pedro formation is exposed along the northeast flank of the Palos Verdes Hills and along the slopes of Baldwin Hills. It extends seaward for some distance beneath the continental shelf in Santa Monica and San Pedro Bays. The Silverado zone is the coarse basal member of the San Pedro formation which underlies most of the West Coast Basin and extends eastward over the Newport-Inglewood uplift where it is continuous with Pleistocene aquifers in the Central Coastal Plain. This productive zone is a distinct confined body of sand and gravel with scattered discontinuous layers of relatively impermeable sandy silt, silt and clay. It is, however, merged with overlying aquifers in the coastal area adjacent to Santa Monica Bay and locally along the Newport-Inglewood uplift. The "400-foot gravel" is apparently an upper section of the Silverado water-bearing zone that is separated by an extensive layer of sandy silt and clay. As a distinct aquifer, it underlies only the central part of West Coast Basin between Inglewood and Gardena. It is not a coarse continuous zone but is identified as a rather variable deposit comprising interbedded layers of sand, sandy silt, and silt and clay.

The principal confined Pleistocene aquifers in the West Coast Basin are recharged by ground water moving southwest across the Newport-Inglewood uplift and to a minor extent by ground water moving south from the flanks of the Santa Monica Mountains. The Newport-Inglewood uplift is the major barrier to ground water movement in the area. Barrier effects are most pronounced across the Inglewood and Potrero faults in the north portion of the basin and across the Avalon-Compton, Cherry Hill, Reservoir Hill, and Seal Beach faults in the southern portion. The Recent water-bearing zones in Dominguez and Alamitos gaps have not been deformed across the uplift, so free flow of ground water can occur in these aquifers between the Central Coastal Plain and the West Coast Basin.

Within the West Coast Basin, the Charnock fault, which parallels the Newport-Inglewood uplift, forms a major barrier to ground water movement in the San Pedro aquifers. This fault does not appear to affect movement in upper Pleistocene aquifers. The barrier effect is most marked north of Ballona Escarpment. Southeastward from Hawthorne, the barrier effect appears to diminish until there is no noticeable effect in the Silverado zone.

There are no known continuous barriers to ground water movement to prevent the intrusion of sea water into the aquifers.

Quality of Water. The principal water courses in the West Coast Basin are Dominguez Channel, Compton Creek, and the Los Angeles River. Since flow in these streams during most of the year is derived substantially from waste discharges, the mineral quality is extremely variable and complex. For this reason and because these streams contribute negligible recharge to the coastal ground water basins, no attempt has been made herein to illustrate the quality of surface flow in these channels.

Under natural conditions, as judged by analyses made in 1931, ground waters of the Gaspur water-bearing zone were of excellent mineral quality. These waters were calcium bicarbonate in character, containing 300 to 400 ppm total dissolved solids, and 75 ppm or less of chlorides. Since 1931, waters in this zone have deteriorated in quality as a result of improper waste disposal practices and sea-water intrusion; and many wells have been abandoned. Wells adjacent to San Pedro Bay have undoubtedly been intruded by sea water, but other inactive wells four to six miles inland show chlorides in the order of 360 to 1,370 ppm and sulfates from 747 to 1,427 ppm. In 1955, active wells produced waters with total dissolved solids content ranging from 260 to 1,428 ppm, with a median of 920 ppm, sulfates from 16 to 434 ppm, with a median of 209 ppm, and chlorides from 23 to 370 ppm, with a median of 189 ppm.

The ground waters of the "200-foot sand" and Gardena water-bearing zone are calcium-sodium bicarbonate and sodium bicarbonate in character. The mineral quality is generally good, but concentrations of chlorides and sulfates are unusually high in localized areas, indicating deterioration from waste disposals or interconnection with poor quality shallow zone waters, either through natural breaks or by improperly constructed or abandoned wells. Total dissolved solids range generally from 150 to 1,300 ppm, with some values as high as 2,570 ppm. Chlorides usually range from 25 to 400 ppm; but have gone as high as 885 ppm.

Waters of the Silverado water-bearing zone and the "400-foot gravel" are generally of excellent mineral quality except where affected by sea-water intrusion. The character is primarily sodium bicarbonate and sodium-calcium bicarbonate. Total dissolved solids are generally less than 650 ppm, chlorides range from 20 to 80 ppm, and sulfates range from zero to 80 ppm. In a few isolated areas, notably near Inglewood and in the vicinity of the intersection of Alameda Boulevard and Dominguez Channel, there are indications of local quality deterioration. In these areas, chlorides, sulfates and total dissolved solids have increased five to ten times the values considered normal in this zone. This deterioration is attributable to the migration of poor quality waters and wastes, either in zones of mergence of aquifers or by means of improperly constructed or abandoned wells.

Mineral analyses of representative samples of surface and ground water are shown in Appendix A.

Status of Sea-Water Intrusion. The present water levels for the confined aquifers underlying the Los Angeles Coastal Plain bear little resemblance to 1904 conditions, when there were many flowing wells and water levels were over 100 feet above sea level in the vicinity of Hawthorne. By 1955, piezometric surfaces for all confined aquifers in the West Coast Basin and parts of adjoining areas were below sea level; and in the vicinity of Hawthorne, the static water level in wells had declined to 90 feet below sea level.

Declining water levels within the basin have been accompanied by a deterioration of ground waters for many years. The earliest intrusion was observed in 1912 in Redondo Beach at the head of Redondo Submarine Canyon, and by 1932 essentially all coastal areas in the basin had been affected. The areal extent of intrusion in 1945 and 1955 is illustrated on Plate 16.

Saline deterioration of ground water within Dominguez and Alamitos gaps has been primarily restricted to the Recent alluvial deposits. The Pleistocene deposits underlying Alamitos gap, immediately landward of the Seal Beach fault, have recently yielded waters of somewhat deteriorated quality. This deterioration may be a result of interconnection of aquifers through the improper construction or maintenance of wells, or downward percolation of saline waters from the overlying Recent deposits which extend continuously across the Seal Beach fault.

Along Santa Monica Bay between Ballona Escarpment and the Palos Verdes Hills, sea-water intrusion has occurred in the major water producing zone of West Coast Basin, the Silverado water-bearing zone. This intrusion presents the most critical problem of the basin, since the entire coastal segment of this aquifer has been affected. Rates of advance of the saline front in the Silverado zone have been somewhat variable. In the vicinity of El Segundo, the saline front has advanced an average of 150 feet per year and at Manhattan Beach about 750 feet per year. Chloride ion increases and fluctuations of water levels at selected wells in the vicinity of Playa del Rey, Manhattan Beach, and Long Beach are illustrated on Plate 15.

The areal extent of sea-water intrusion during 1955 is depicted on Plate 16. However, degradation within these defined areas may have partially resulted from a deteriorant other than sea water. Discharges of oil field brines and industrial wastes into Compton Creek, Dominguez Channel, and the Los Angeles River have contributed to the degradation of ground waters in the vicinity of these streams; and have complicated the problem of isolating the specific effects of sea-water intrusion.

During the spring of 1955, water levels within the Pleistocene aquifers were below sea level throughout the West Coast Basin and beyond. It is conceivable that sea water could advance to the limit of this area; however, many physical and artificial barriers exist to prevent such an advance. Within the West Coast Basin, a pumping trough exists east of the Charnock fault and extends southeasterly from Ballona Escarpment toward Dominguez gap, which would impede the advance of a saline front. In the Long Beach area, the Cherry Hill, Reservoir Hill, and Seal Beach faults have presumably prevented the flushing of connate water from permeable Pleistocene deposits underlying the Long Beach Plain, and could similarly restrict landward intrusion.

The Silverado zone underlying Dominguez gap extends an unknown distance beneath San Pedro Bay and either pinches out adjacent to impermeable Tertiary deposits or contains sufficient storage of undeteriorated water so that sea-water intrusion has not as yet been observed in wells near the coast. The overlying Gaspur zone, however, is not completely isolated from Pleistocene aquifers, and could provide access for saline deteriorants.

East Coastal Plain Pressure Area

The East Coastal Plain Pressure Area is the seaward portion of the coastal plain of Orange County. It stretches from the Los Angeles County line southeasterly to the San Joaquin Hills, a distance of approximately 16 miles, and extends from 8 to 12 miles inland. The coast line is bordered by flat low hills which have been dissected by the drainage across the coastal plain to form a series of mesas and alluvium-filled gaps. Progressing southeasterly from the Los Angeles-Orange County line these features are generally known as Alamitos gap, Landing Hill, Sunset gap, Bolsa gap, Huntington Beach Mesa, Santa Ana gap, and Newport Mesa. Alamitos gap extends into the West Coast Basin. The gaps are particularly significant since they are underlain by alluvium through which sea water may advance inland when conditions are favorable. The investigational area is shown on Plate 16.

At present, agriculture is a major activity in Orange County but residential subdivisions are rapidly encroaching upon farm land. Population in the County is increasing rapidly. Major industrial activities in Orange County include oil refining, packing and processing of citrus fruits, boat building, and fishing.

Although the early agricultural developments in Orange County relied upon surface diversions from Santa Ana River and Santiago Creek, ground water is now the principal source of water supply. Artificial recharge operations have been conducted in the forebay area for many years, using local runoff. Increasing draft on the ground water basins and declining ground water levels caused the major cities in Orange County to join The Metropolitan Water District; and Colorado River water has been imported since 1941 for municipal use. In 1949, the Orange County Water District started spreading unsoftened Colorado River water in the Santa Ana River channel. This recharge program was augmented by the Orange County Flood Control District and continued by the Orange County Municipal Water District. From the date of initial import in 1941 through June 30, 1957, a total of 584,000 acre-feet of Colorado River water has been purchased for direct municipal use and ground water recharge. Despite these imports, ground water levels remain below sea level throughout most of the East Coastal Plain Pressure Area.

Occurrence and Movement of Ground Water. The water-bearing deposits underlying the East Coastal Plain Pressure Area include sediments of Recent, Pleistocene and Pliocene ages. In general, the sediments occur as interfingering lenses of gravel, sand, silt, and clay. Two water-bearing zones have been differentiated within the Recent sediments, three in the Pleistocene deposits, and one in the Pliocene deposits. These aquifers are depicted by geologic sections on Plate 18.

The Recent alluvial deposits are divided into an upper and lower portion. The upper portion is composed of silt, sand, and gravel of fluvial origin with interbedded lenses of fine sand, silt, and clay of lagoonal origin near the coast. The lower portion of the Recent deposits contains the coarse grained Talbert water-bearing zone and the "80-foot gravel."

The Talbert water-bearing zone is composed of a tongue of coarse sand and gravel extending from the coast through Santa Ana gap into the forebay area. This aquifer varies in thickness from 40 to 100 feet; and its base is approximately 160 feet below sea level at the coast. The "80-foot gravel" extending from the coast through the Bolsa gap, is composed chiefly of coarse sand and gravel varying from 5 to 20 feet in thickness. Inland from the gap, it merges with the Talbert zone. Its base is encountered from 60 to 90 feet below sea level.

Unnamed upper Pleistocene deposits comprise the surface of the mesas and underlie the Recent materials in the East Coastal Plain Pressure Area. These deposits are composed of fine sand and silt with lesser quantities of coarse sand and gravel; and are generally considered to be of fluvial, lagoonal, and shallow marine origin. The upper Pleistocene deposits are deformed along the Newport-Inglewood uplift, dipping generally inland and oceanward from the uplift.

The lower Pleistocene San Pedro formation underlies the entire East Coastal Plain Pressure Area with the exception of the southeastern portion of Newport Mesa. These deposits are of marine origin and are composed of relatively thick extensive beds of coarse sand and gravel, silt, and lesser quantities of clay. The San Pedro formation has been deformed almost everywhere along the Newport-Inglewood uplift and dips from the uplift inland into the basin.

Underlying the San Pedro formation is the upper portion of the Pico formation of Pliocene age, which contains numerous zones of fine to medium-grained sand separated by thin beds of siltstone. The Pico contains some fresh water and is tapped by a few wells of low yield.

Recharge of the aquifers of the East Coastal Plain Pressure Area occurs chiefly in an intake or forebay area near Anaheim, where recharge is effected by infiltration from the Santa Ana River channel. Percolating water enters the Talbert zone and, in part, passes into the underlying Pleistocene and Pliocene aquifers. Under natural conditions, ground water moved in a southerly direction through the several aquifers, discharging ultimately to the ocean.

The Newport-Inglewood uplift is the only significant ground water barrier within the region. This geologic structure comprises a group of en-echelon faults and folds extending in a northwesterly direction. The uplift has little effect upon the movement of ground water within the Recent deposits but does act as a partial barrier to subsurface flow within the Pleistocene and older sediments. Movement of ground water is retarded by zones of cementation and gouge located along the fault planes, and by lithologic discontinuities.

Heavy pumping has depressed ground water levels below sea level throughout most of the East Coastal Plain Pressure Area. The resulting piezometric surface forms a trough, the axis of which parallels the coast about five and one-half miles inland. The position of this trough axis and the line delimiting the extent of the area beneath which ground water levels were below sea level in 1955 are shown on Plate 16. The trough axis is significant inasmuch as it marks the limit to which sea water would intrude were these pumping conditions maintained. However, this limit is in no way fixed, as a change in the pattern of pumping could shift the position of the axis and consequently establish a new theoretical limit for sea-water intrusion.

Quality of Water. There is little surface flow in the East Coastal Plain Pressure Area; and consequently no attempt is made herein to discuss its quality. The character of ground waters in and adjacent to the forebay area is generally calcium bicarbonate. These waters are suitable for domestic use and are considered to be Class 1 for irrigation use. Total dissolved solids content ranges from about 200 to 600 ppm and the chloride concentrations are usually less than 50 ppm. Hardness ranges from about 130 to 350 ppm and boron content is less than 0.2 ppm.

Seaward of the Newport-Inglewood uplift, ground waters are generally of a sodium to calcium chloride character and approach sea water in quality. They are unsuitable for domestic or irrigation use. Where not impaired by oil field brines or sea-water intrusion, ground waters within the Pleistocene deposits inland of the uplift are dramatically different in character and quality, generally exhibiting a calcium or sodium bicarbonate character. These waters are generally suitable for domestic and irrigation use, although they range from soft to very hard in character. The total dissolved solids content of these waters is usually less than 400 ppm, the chloride concentration generally less than 50 ppm and hardness less than 350 ppm. The boron content does not exceed 0.2 ppm.

Waters inland of the fault zone in the areas of Huntington Beach Mesa and Santa Ana gap, however, have been impaired by the percolation of oil field brines, intrusion of sea water, and the migration of connate waters. Within these areas, the waters are calcium chloride to sodium chloride in character and extremely variable in quality. These waters contain excessive chloride and total dissolved solids concentrations which generally render them unsuitable for domestic and irrigation uses. There are other areas along the uplift, notably Alamitos gap and Bolsa Chica Mesa, where deterioration of water quality has occurred, but data are not sufficient to determine the cause or causes. Representative mineral analyses of ground water are shown in Appendix A.

Status of Sea-Water Intrusion. Sea-water intrusion is a major cause of degradation of ground waters in the East Coastal Plain Pressure Area. In addition, increased salinity also appears to be a consequence of the disposal of industrial waste, oil field brines, extensive re-use of ground water, migration of connate water, and deterioration in the quality of inflow to the basin. These factors are mentioned because their effects are sometimes erroneously attributed to sea-water intrusion. With the exception of connate waters and industrial wastes, however, the effects of these factors are insignificant in comparison to the rapid salinity rises caused by sea-water intrusion.

The salinity of ground waters underlying portions of Newport Mesa and adjacent areas and underlying the strip between the coast line and the Newport-Inglewood uplift is attributed chiefly to the presence of connate brines. In these areas, ground water of poor quality existed before landward hydraulic gradients were established and before significant quantities of oil had been produced. Therefore, this degradation could not have been due to the disposal of brines or to sea-water intrusion, although subsequent deterioration of water quality in these areas has probably been influenced by both of these factors.

Long time residents of Huntington Beach Mesa report that ground water beneath the mesa became saline as early as 1925, five years after discovery of the Huntington Beach Oil Field and 22 years before a continuous landward hydraulic gradient was established. Furthermore, there are localized areas of high ground water salinity beneath the mesa or beneath areas immediately adjacent to the mesa, which are indicative of improper disposal of oil field brines. Such observations indicate that the initial manifestations of ground water degradation in this locality were probably the result of the disposal of oil field brines on the surface of the ground, possibly augmented by interconnection of aquifers by improperly constructed oil wells.

The Ground Water Branch of the United States Geological Survey has, in cooperation with the Orange County Flood Control District and Orange County Sanitary District, made studies of the status of salt-water intrusion in Orange County. In their reports, they noted that sea-water encroachment began as early as 1942 in Alamitos gap and that in Santa Ana gap 275 acres were underlain by sea water in 1944.

The Talbert zone underlying Santa Ana gap has been seriously affected by the intrusion of sea water, and many wells have been abandoned because of excess salinity. By 1955, the saline front extended inland more than two miles, as shown on Plate 16, and is steadily advancing. Changes in chloride ion concentration and water level fluctuations in wells are illustrated graphically on Plate 15.

Mission Basin

Mission Basin, delineated on Plate 19, is the westernmost and largest of several elongated basins that lie along the San Luis Rey River in the northern portion of San Diego County. It is a shallow alluvium-filled valley extending about eight miles inland from the Pacific Ocean. The valley floor ranges in elevation from sea level to about 100 feet at its eastern limit. San Luis Rey Canyon, located at the extreme western end of the basin, is a narrow, steep-walled gorge extending inland from the coast about two miles where it enlarges to a width of approximately one mile. The canyon constitutes the only outlet for surface drainage from the basin.

Ground waters of Mission Basin are presently utilized for domestic and agricultural purposes on overlying lands. Both the City of Oceanside and the Carlsbad Mutual Water Company pump and export ground water from this basin for municipal and agricultural purposes. The continued draft on this relatively small ground water basin, during the period of subnormal rainfall and runoff which started in 1945, has lowered ground water levels throughout most of the basin. In January, 1956, ground water levels were below sea level approximately five miles inland from the coast, as shown on Plate 19.

Because of lowering ground water levels and depreciation in quality, both the City of Oceanside and the Carlsbad Mutual Water Company import Colorado River water through facilities of the San Diego County Water Authority to supplement the local supply. The total import by both agencies was 14,900 acre-feet during the period from 1950 to June 30, 1957.

On July 2, 1957, voters in the City of Oceanside passed a bond issue to finance construction of a sewage reclamation project. Water reclaimed from sewage is used for industrial purposes and also to recharge ground waters of Mission Basin.

Occurrence and Movement of Ground Water. Recent alluvium in Mission Basin was deposited in an ancestral channel of the San Luis Rey River carved in the geologic past, when sea level was about 300 feet below its present elevation. The logs of wells reveal a zone of fine sand, silt or clay generally extending from the surface to depths of about 100 feet, in all but the eastern end of the basin. Underlying these fine-grained materials are about 100 feet of highly permeable gravels and coarse sands which constitute the principal pumping zone.

The walls and floor of the basin are older sedimentary formations, which are much less permeable than the alluvium. San Luis Rey Canyon is cut in resistant, firmly cemented conglomerate, the San Onofre breccia. The La Jolla formation flanks and generally underlies the recent alluvium throughout the remainder of the ground water basin. This formation consists of sedimentary materials deposited in a marine environment and subsequently elevated to their present position. The formation is slightly permeable, and contains brackish or saline ground water, possibly due to the presence of sea water as yet not entirely flushed from the formation.

Under natural conditions, ground water flowed westward through the basin and discharged to the ocean through the gravels in San Luis Rey Canyon. At present, heavy pumping has lowered ground water levels below sea level and a landward gradient has been established. A comparison of historic water levels at wells indicates that a pumping trough has existed continuously near the center of the basin since 1948. The axis of the pumping trough is shown on Plate 19.

Quality of Water. Surface runoff in Mission Basin is sodium chloride in character and of good mineral quality. Representative analyses are shown in Appendix A.

Ground waters of Mission Basin are subject to marked degradation from saline connate waters in underlying and surrounding formations, and sea water. Degradation from both of these sources is influenced by ground water levels. As levels are lowered, mineral concentrations increase; and the predominant anion changes from bicarbonate to chloride. Careful evaluation of quality changes and water level changes indicates that quality deterioration in the lower portion of Mission Basin near San Luis Rey Canyon is caused by sea-water intrusion. Deterioration of ground water in the remainder of the basin is caused primarily by connate water from adjacent and underlying formations and in part by use and re-use of water. Mineral analyses of typical ground waters in Mission Basin are shown in Appendix A.

Status of Sea-Water Intrusion. A 7,000 ppm rise in the chloride ion concentration in ground water at well No. 11S/5W-23E1 during the period 1951-52 through 1954-55 is interpreted to indicate the arrival of sea water in the immediate vicinity. This well, located in San Luis Rey Canyon approximately 4,000 feet from the ocean, supplies wash water for a sand and gravel plant. These wash waters are discharged to tailings ponds in the alluvium located upstream of the supply well and only about 700 feet from well No. 11S/5W-14Q1. Chloride increases at this latter well could be caused by sea-water intrusion or gravel plant operations, or both. The gravel plant operation, whereby diluted ocean water is finally discharged as wash water further inland, affects the hydraulic gradient and rate of sea-water intrusion into the western end of Mission Basin. Salinity increases and ground water level fluctuations in wells Nos. 11S/5W-14Q1 and 11S/5W-23E1 are shown on Plate 20.

Low water levels further inland have also been an important factor in causing sea-water intrusion. As shown on Plate 20, the hydrograph of well No. 11S/5W-13N1, located about 11,000 feet from the ocean, indicates that the water level at that point first receded below sea level in August, 1949, and has remained below sea level since that date, with the exception of brief periods in December, 1949; January, 1950; and March, April, and May of 1952. These observations indicate that sea-water intrusion could have commenced as early as August, 1949. Extent of the 100 ppm isochlor in January, 1956, is shown on Plate 19.

CHAPTER IV

METHODS OF CONTROL OF SEA-WATER INTRUSION

In the light of present knowledge and experience there are five principal methods for the prevention and control of sea-water intrusion. These are:

(1) Raising of ground water levels to or above sea level by reduction in extractions and/or rearrangement of areal pattern of pumping draft;
(2) Direct recharge of overdrawn aquifers to maintain ground water levels at or above sea level;
(3) Maintenance of a fresh water ridge above sea level along the coast;
(4) Construction of artificial subsurface barriers;
(5) Development of a pumping trough adjacent to the coast.

It should be noted that implicit in all methods of control is the necessity for elimination of overdraft on the ground waters of the basin by some means. Assurance of an adequate water supply to support the economy of lands now dependent upon the local basin water supplies, without impairment, must be a primary consideration in any program for control of sea-water intrusion. This may involve importation of supplemental water from nontributary sources, or additional conservation of local supplies, or both. Maintenance of, and, if possible, increased conservation of locally available water resources generally would be a major factor in the formulation and application of a program for control of sea-water intrusion.

The objectives of any control program should be to prevent further encroachment, and, if possible, to reduce the area already affected by sea-water intrusion. Each coastal ground water basin is unique as regards hydrologic and geologic characteristics. Therefore, only generalizations can be discussed herein. A comprehensive engineering, geologic, hydrologic, and water quality investigation must be undertaken to obtain the information necessary for a proper determination of the method or methods of control to be used. This investigation should be programmed to delineate the characteristics of the water- bearing formations, evaluate ground water conditions, and to examine the engineering and economic problems associated with changing the regimen of ground water extractions and development of supplemental supplies. Legal problems regarding water rights may also require investigation.

In evaluating the economic feasibility of the various methods of control the following factors, among others, must be taken into account: the cost of obtaining and distributing supplemental water, including the expense of any necessary treatment; the value of storage capacity in the ground water basin; the cost of necessary physical works; the cost of pumping water from the basin; and, in some instances, the value of the ground water basin as a source of emergency supply and as a distribution system. The total net costs of preventing sea-water intrusion, by one or a combination of methods involving the construction and operation of physical works, must be balanced against the cost of decreasing extractions from the basin to the necessary extent and using supplemental water directly on the surface.

RAISING OF GROUND WATER LEVELS TO OR ABOVE SEA LEVEL BY REDUCTION IN EXTRACTIONS AND/OR REARRANGEMENT OF AREAL PATTERN OF PUMPING DRAFT

This method requires that the pumping draft be altered sufficiently, either by reduction in extractions, by rearrangement of areal pattern of pumping, or both, so that ground water levels will rise to or above sea level and be maintained there, except possibly for infrequent periods of short duration. A seaward hydraulic gradient must be established and maintained. Insofar as is now known, this method, while not necessarily the most desirable from the standpoint of the water user, would probably always be effective in any coastal ground water basin.

Although it is manifest that reduction in pumping draft would tend to effect a rise in ground water levels, additional comment is warranted regarding effects of rearrangement of the pumping pattern. Depressions in the piezometric or free ground water surface are formed as a result of withdrawals of ground water. The configuration, depth, and lateral extent of these depressions are dependent upon the rate and location of withdrawals. Thus, if the location of major withdrawals is transferred from the coastal segment of a basin to an area further inland, the pumping trough would tend to move inland also, the landward hydraulic gradient on the ocean side of the trough would be flattened, and the seaward gradient inland from the trough would be increased. Such a condition would tend to slow or halt the inflow of saline water and increase fresh-water replenishment. In most of the major intruded ground water basins of the State, withdrawals along the coastal margins are from confined aquifers which are replenished mainly by underflow from inland forebay areas of free ground water where natural or artificial recharge occurs. A transfer of location of withdrawals to these free ground water areas could tend to increase this recharge by increasing the available subsurface storage. At the same time the landward gradient from the sea would be flattened and possibly eliminated. Construction of a surface distribution system would be necessary to serve the areas in which extractions from the underlying ground water had been reduced or stopped.

The initial step in any program involving reduction in pumping draft and/or relocation and rearrangement of pattern of pumping must be the determination of the basic water rights of the individual water users of ground water in the basin. The salient geologic and hydrologic features in the basin necessary for the determination of a long-term basin-wide balance of draft and replenishment must be determined by adequate investigation. Under present California law, reduction in pumping or rearrangement of the pumping pattern could be achieved only by agreement or under a court decree. A necessary prerequisite to initiation of this method of control, where total draft of ground water is to be reduced, would be the existence of a source of supplemental water supply at reasonable cost, sufficient in quantity to equal reduction in ground water draft and provide for future expansion, and of suitable quality. It is pointed out that in some instances this method would not allow the full development and utilization of the available ground water storage capacity. In some basins, raising the water levels would decrease the inflow or supply to the basin; and escape from the basin, particularly flood waters, might be increased. The West Coast Basin in Los Angeles County is an example in which decreased inflow to the basin will occur with reduction in draft, unless pumping draft on the basin upstream is concurrently reduced. In this basin, subsurface inflow westward from the Central Coastal Basin across the Newport-Inglewood uplift constitutes a large part of its fresh-water replenishment. Water levels on the upstream side of the fault zone are now below sea level throughout the greater portion of its length, and are progressively dropping. It is therefore obvious that raising the water levels above sea level in the West Coast Basin only on the downstream side of the fault would greatly reduce the differential in head; and it is conceivable that the direction of flow might even be permanently reversed. There are indications that this condition may already exist along portions of the northern section of the fault. Under this condition, the permissible draft on the ground water west of the fault would be limited to the small present recharge from other sources, further reduced by the increased subsurface outflow westward to the ocean and eastward across the fault.

Costs

Capital and annual costs of raising ground water levels above sea level by reduction or rearrangement of the pattern of pumping draft would be dependent on many factors. If the pattern of pumping remained unchanged, but pumping draft were reduced, it would be necessary to provide supplemental water to users within the basin, and the costs connected therewith would be chargeable against the sea-water intrusion control program. These costs would be partially offset by decreased pumping costs as a result of higher ground water levels.

If increased ground water pumping in inland areas resulting from a change in the withdrawal pattern necessitated well drilling, cost of drilling and equipping new wells should also be charged against the control project, as well as the cost of distributing the alternate supply to coastal areas. Compensation to coastal pumpers for their investment in well pumping facilities, the use of which would be greatly curtailed or terminated by a transfer of pumping to inland areas, should be considered, as should recompense to present pumpers in inland areas experiencing increased pumping lifts and attendant higher pumping costs.

Since unit costs would depend on the number, size, and depth of wells, type of well construction and equipment, power costs, and proximity of surface water supply to points of use, which would vary considerably from area to area, it is not considered feasible to develop such cost data herein.

DIRECT RECHARGE OF OVERDRAWN AQUIFERS TO MAINTAIN GROUND WATER LEVELS AT OR ABOVE SEA LEVEL

This method requires that ground water levels in the overdrawn aquifers be raised and maintained above sea level by artificial recharge, utilizing surface spreading, injection wells, or both. In most instances, supplemental water from nontributary sources would be necessary, although for some basins additional conservation of tributary runoff could be achieved by providing sufficient upstream regulatory storage to permit artificial recharge. Rearrangement of the pattern of pumping draft might, under certain circumstances, facilitate use of this method and reduce the total cost involved.

In order to implement this method of control, a detailed engineering and geologic investigation would be required to determine draft on the basin; location and extent of aquifers; ground water depths and movement; natural recharge and losses; quantity of water necessary; sources and quality of water available for recharge and its cost; and determination of the degree and cost of necessary prior treatment. It would be necessary to determine proper location of surface spreading sites or injection sites, with respect to surface and subsurface geology of the ground water basin, so as to obtain maximum sustained percolation rates, and the most efficient utilization of storage capacity. Consideration must also be given to pattern of pumpage, to ascertain that transmissibility of the aquifer is adequate to assure necessary flow of ground water from areas of recharge to centers of pumping draft.

This method requires that water be made available for recharge in sufficient quantity and of suitable quality over a continuing period of time and at a reasonable cost. Where injection through wells is necessary, water quality is a consideration of primary importance. Although the total cost of this method of control would probably be high for many coastal ground water basins, because of the high cost of project works, rights of way, operating expense, necessity for providing expensive storage and distribution systems, and need for treating recharge water, particularly if injection wells were used, it does offer certain advantages to the water users in the basin. If it is found feasible to maintain ground water levels above sea level by artificial recharging, without any change in pumping draft, it is possible that no control of pumping would be necessary. One additional advantage gained by this procedure is that in or near metropolitan areas such as San Francisco, Los Angeles and San Diego, reclaimed waste waters of suitable quality could be utilized.

There are several disadvantages, in addition to those of high initial cost and operating expense. The usable storage capacity of a ground water basin is decreased if water levels throughout the basin are continuously maintained above sea level by artificial recharge. Furthermore, the same basic problem exists as in the previously discussed method involving decrease in extractions, in that in some ground water basins raising of water levels would decrease the inflow or supply to the basin, while outflow or escape from the basin might be increased.

Costs

Two principal elements of cost are involved in this method, first the cost of the water itself, including the cost of any necessary pretreatment; and second, the cost of the actual recharging operation. Where upstream regulatory storage is necessary to utilize local runoff for artificial recharge, the cost of water may be as high as it generally will be with imported water. Any necessary rearrangement of pumping draft would add to the cost.

Since storm runoff has been spread at existing artificial recharge projects for many years, certain cost data on direct recharge of aquifers are available. One of the most important factors influencing cost of recharge is property acquisition, which is becoming more costly, especially in areas where urban development is rapidly expanding. The Los Angeles County Flood Control District, which operates 23 artificial recharge projects, reports that recent costs of property acquisition have varied from $1,000 to $6,500 per acre.

This District further reports that annual maintenance costs at their major projects have averaged about $37 per gross acre of project. Total costs of spreading storm runoff, including interest and amortization on capital outlay, have varied from approximately $4.50 per acre-foot during years of above normal runoff to about $9.00 per acre-foot during drought periods. Amortization is based on a 10-year life for wooden structures, 50-year life for concrete structures, and an interest rate of four per cent per annum. Operation and maintenance costs of spreading imported Colorado River water have not exceeded $2.30 per acre-foot, including the cost of patrolling the stream channel used to convey the water but excluding the cost of the water and interest and amortization charges. All of these averages are based on actual expenditures; and have not been corrected to a common cost basis.

Where relatively impermeable sediments overlie an aquifer, recharge must be conducted through use of injection wells. Cost information obtained from well drilling at the pressure ridge field experimental project in the West Coast Basin, Los Angeles County, subsequently described, indicates that the average cost of drilling and developing eight nongravel-packed 12-inch wells, using the cable tool method and 12 gauge, double, hard red steel casing, to an average depth of about 265 feet, was approximately $17 per foot of depth. Cost of gravel-packed wells with 12-inch casings varied from about $29 to $35 per foot of depth, depending upon method of construction. Cost of drilling and developing 36 eight-inch nongravel-packed wells, with double, hard red steel casing, to an average depth of about 310 feet, approximated $9 per foot of depth. These costs are believed to be slightly higher than average, since the project was experimental in nature and costs included coring and grouting.

The Los Angeles County Flood Control District estimated the annual cost of redeveloping a gravel-packed recharge well to be approximately $500, and cost of chlorine to treat five second-feet of previously filtered and chlorinated water with a dosage of eight parts per million to be $4,500 per year. Where reclaimed waste waters are proposed to be used, the cost of prior treatment is a major factor.

MAINTENANCE OF A FRESH-WATER RIDGE ABOVE SEA LEVEL ALONG THE COAST

This method would require the continuous maintenance of a fresh-water ridge in the principal water-bearing deposits along the coast, through the application of water by surface spreading or injection wells or both.

In order to implement this method of control, a detailed engineering and geologic investigation would be required to determine the most satisfactory location of the line of injection wells or surface spreading sites. Certain key factors must be determined, including location, extent and characteristics of aquifers; depth to base of aquifer; degree of confinement and physical characteristics of confining members; transmissibility of aquifers; hydraulic gradients; amount and pattern of pumping draft; sources and amount of present recharge to the basin; and location of area of degraded ground water. All of these aspects plus others must be known, in order to determine the shape and height of ridge required, and recharge rates necessary for its maintenance.

This method is also predicated upon the assumption that a source of water supply of sufficient quantity and quality for recharge could be made available over a continuing period of time, and at reasonable cost. In general, this would necessitate the importation of water from nontributary sources. However, where additional conservation of local water resources could be achieved by increase in availability of ground water storage, at least a portion of the water required for maintenance of the ridge might be obtained by pumping from the ground water basin

The actual formation of a ridge along the coastal segment of a ground water basin by the use of injection wells or by surface spreading, or a combination of both methods, would depend on whether free ground water or pressure conditions exist, as determined by detailed engineering and geologic investigation. In basins where free ground water conditions exist along the site of the proposed ridge, a mound of more or less uniform height could probably be maintained by continuous application of water in spreading grounds. In basins where pressure conditions exist and injection wells are utilized, the ridge would consist of a series of peaks with saddles between. In either case, the required elevation of the ridges and saddles above sea level would be determined by the distance of the base of the aquifer below sea level, its transmissibility, the height of fresh-water head necessary to displace sea water to the base of the fresh-water-bearing deposits, and the existing hydraulic gradient in the aquifer. Here again, rearrangement of the pattern of pumping draft might be beneficial. Extractions from the basin would have to be brought into balance with the total usable recharge to the basin including the flow landward through the aquifer from the ridge.

This method of control offers many advantages. If continuously maintained, such a fresh-water ridge just inland from the coast would be as effective in repelling sea-water intrusion as would a seaward hydraulic gradient extending entirely across the basin. There would, of course, be some waste of water to the ocean. In some basins such as Tia Juana Basin and the San Luis Rey and Santa Margarita Valleys, where the safe yield from natural sources under present conditions is limited by the storage capacity available above sea level, it would permit greater lowering of the water table landward from the ridge, thus adding to the usable underground storage capacity and making possible the salvage of water now wasting after the basin fills. In the West Coast Basin and similar basins this method would be advantageous since the differential in head across the Newport-Inglewood fault zone, which induces inflow from the Central Basin, could be maintained indefinitely. In some basins, interference with the existing pattern of extractions might not be great.

Initial expenditures and operating costs would be relatively high, but probably not as great as would be incurred in attempting to maintain water levels above sea level throughout the entire basin by direct recharge of aquifers. It is possible that reclaimed waters of suitable quality could be used to maintain such a mound or ridge. Use of such waters may be the only economically feasible solution in many ground water basins where intrusion has already occurred or may soon occur. Where injection wells are to be used, water quality is of primary importance.

Costs

In 1955, the Los Angeles County Flood Control District reported that a pressure ridge project in the West Coast Basin, along an 11-mile reach of coast line adjacent to Santa Monica Bay, would involve a capital cost and annual operation and maintenance cost per mile of recharge line of \$186,000 and \$32,000, respectively. These costs do not include the cost of recharge water, right of way, or feeder lines from a water supply to the recharge line. It is estimated the cost of water per mile of reach would be in the order of \$54,000 per year, assuming water charges at \$12 per acre-foot. Costs of rights of way and feeder lines per mile of reach would probably be in the order of \$5,000 and \$23,000, respectively. This proposed project is discussed in some detail later in this report.

CONSTRUCTION OF ARTIFICIAL SUBSURFACE BARRIERS

This method involves the establishment of a subsurface barrier to reduce the permeability of the water-bearing deposits sufficiently to prevent the inflow of sea water into the fresh-water strata. This reduction in permeability could be achieved by the construction of a subsurface barrier composed of sheet piling, a puddled clay cutoff wall, or some other form of physical structure. Emulsified asphalt, cement grout, bentonite, silica gel, calcium acrylate, plastics and other materials might be injected to form a vertical zone of reduced permeability which would retard or prevent intrusion of sea water. Implementation of this method of control would require a detailed engineering and geologic investigation of location, extent, thickness, depth and physical characteristics of water-bearing deposits adjacent to the coast. It would be necessary to determine total cross-sectional area of the cutoff wall and characteristics of the materials involved.

This method of control offers many advantages, particularly for the numerous narrow coastal ground water basins where the principal aquifers occur at relatively shallow depths. A subsurface barrier would probably be permanent, no operation would be required, and maintenance costs would be low. A major advantage is that the locally available ground water resources, ground water storage capacity, and tributary surface runoff could be exploited to a maximum degree. The requirement for supplemental water from nontributary sources could thus be held to a minimum. Use of the barrier method would cause minimum interference with existing rights, since major changes in pumping pattern, and/or reduction of ground water extractions, would not necessarily be required; although a change in pumping pattern might be desirable to maintain quality in the lower portions of the basin, and/or prevent waterlogging of lands immediately upstream from the barrier. Such a barrier would permit greater development and utilization of the storage capacity of the basin and thus increase the yield.

There are several disadvantages to this method of control, including high initial construction costs; physical limitations on depths to which it is practicable to construct barriers; need for exportation of some water from the basin to maintain favorable salt balance, since comparatively little flushing of the basin would occur even during wet periods; and reduction in fresh water supply available to wells downstream from the barrier.

Costs

Outstanding examples of the puddled clay cutoff wall have been installed at Wilmington, California, and Kennewick and Pasco, Washington. These projects are described in the succeeding chapter of this report, and their costs are presented herein as indicative of this type of construction.

The Wilmington project contained over 18,000 feet of wall, ranging in depth from 15 to 45 feet below land surface, and was built at a cost of $2.50 per square foot of wall in a vertical plane.

Actual costs for a levee cutoff wall constructed along the left bank of the Columbia River in the vicinity of Pasco were as follows:

Description	*Quantities, in square feet*	*Unit price, per square foot*	*Total cost*
Cutoff from 0 to 20 feet in depth	630,881	$0.21	$132,485.01
Cutoff from 20 to 30 feet in depth	226,279	0.40	90,511.60
Cutoff from 30 to 40 feet in depth	92,638	0.43	39,834.34
Cutoff over 40 feet in depth	20,836	0.51	10,626.36
Compensation for unexpected subsurface conditions	----	lump sum	1,150,000.00
Totals	970,634		$1,423,457.31

It should be noted that about 80 per cent of the total cost at Pasco was attributable to unexpected subsurface conditions, such as caving of trench sides, excessive seepage of water, and cemented sands and gravels.

The Kennewick project, located along the right bank of the Columbia River directly opposite from Pasco, utilized two methods of trench excavation. Where walls of the trench were unsupported, the following costs were entailed:

Description	*Quantities, in square feet*	*Unit price, per square foot*	*Total cost*
Cutoff from 0 to 20 feet in depth	463,794	$0.42	$ 194,793.48
Cutoff from 20 to 30 feet in depth	103,216	0.45	46,447.20
Cutoff from 30 to 40 feet in depth	35,940	0.33	11,860.20
Cutoff below 40 feet in depth	10,742	0.21	2,255.82
Subtotals	613,692		$ 255,356.70
Excess cutoff construction	233,250 C.Y.	$3.59/C.Y.	$837,369.65
Total cost			$1,092,726.35

Because of difficult subsurface conditions, a bentonite slurry was utilized to stabilize trench walls for part of this project. The quantities and costs involved in this section are as follows:

Setting up new process	$ 220,942.98
348,920 sq. feet @ $2.8706/sq. ft.	1,001,609.75
Total cost	$1,222,552.73

As in the Pasco project, a major part of the cost, where trench walls were unsupported, represented excess excavation. Progress was limited to about 10 lineal feet per day in the unsupported section, as compared with an average of 90 feet per day where bentonite slurry (Wyatt method) was used.

In 1952, as part of this investigation, the cost of constructing a puddled clay cutoff wall, 1,115 feet long at the surface, at the mouth of the San Luis Rey River near Oceanside, California, was estimated to be $414,000, based primarily on an estimate furnished by the Macco Corporation. This estimate is itemized as follows:

Exploratory drilling	$19,000
Construction of cutoff wall	300,000
Core drilling	30,000
Testing of cutoff wall	25,000
Consulting services	10,000
Engineering and supervision	30,000
Total	$414,000

Based on an average depth of 182 feet and a length of 1,115 feet, the cost per square foot of vertical wall was $2.04. The cost estimate was based on the following construction plan:

1. The top 16 feet of material, down to ground water level, would be removed by dozers and scrapers.
2. A 3-foot wide, 60-foot deep ditch would then be excavated by using a trencher already developed for deep excavation. It would have been necessary to modify this machine by widening the buckets and extending the ladder.
3. The remainder of the 182-foot deep trench would be excavated by using a special clamshell. The clamshell would be of heavy fabrication, and the jaws would be actuated hydraulically or electrically and independently of hoist cable.
4. During trenching and clamshell operation, the ditch would be kept full of bentonite slurry to retain the vertical walls.
5. The excavated material would be mixed with 30 per cent of bentonitic slurry from the trench by pugmill, and would then serve as backfill, thus creating an impermeable barrier.

From the foregoing, it appears that construction of a puddled clay cutoff wall to depths of 200 feet, more less, may be physically feasible.

Aquifer permeability has been reduced through grouting with cement, chemicals, silts, and asphalts, but cost data for such projects are either not available or are not considered applicable to sea-water intrusion barriers. However, it has been reported that, in general, costs of grouting with chemicals are approximately two to three times the costs of cement grouting. It has been further reported, as later mentioned, that costs of materials and placement for grouting at Great Falls Reservoir, Tennessee, averaged $1.19 per cubic foot and $1.35 per cubic foot for cement and asphalt, respectively.

DEVELOPMENT OF A PUMPING TROUGH ADJACENT TO THE COAST

This method would require the continuous maintenance of a pumping trough along the coast in order to create a seaward hydraulic gradient over most of the ground water basin. The required installation and operation would be costly; and unless there was a demand for the mixed ocean and fresh water which would be pumped, considerable quantities of usable water would be wasted. It is believed that the only situation where permanent utilization of this method might be justified would be in a ground water basin where the recharge in itself is sufficiently saline to require the waste of substantial amounts of water for maintenance of salt balance. This procedure might be applied temporarily where encroachment of sea water is far advanced, to stop further intrusion before applying a more permanent method of control.

Costs

Since a pumping trough parallel to the coast to halt sea-water intrusion has never been produced under field conditions, cost information is not available. Order of magnitude of costs can be estimated in a preliminary fashion by adjusting cost data obtained from the pressure ridge experiment in West Coast Basin. Capital charges for the pressure ridge should be increased by the cost of pumping equipment. Annual operation and maintenance expense for the pressure ridge should be increased by the cost of power for pumping. Another major increase in pumping trough costs might result from the fact that imported water, required for direct distribution in conjunction with the pumping trough, would probably be more costly than reclaimed waste water that could be utilized for the pressure ridge. Other adjustments of lesser magnitude, such as a deduction from pressure ridge charges of the cost of chlorinating injection water, which would not be needed for the pumping trough, might also be required.

COMPARISON OF COSTS

For comparison purposes, the general orders of magnitude of costs of the five methods of control have been estimated for a one-mile reach of coast. It was assumed that the depth of the base of the aquifer to be protected averaged about 225 feet, similar to the Silverado water-bearing zone in the West Coast Basin. Although such depths are at or above the upper limit considered within the limits of subsurface barrier construction, for purposes of comparison, it was assumed that barriers could be constructed to the aforementioned depths. It was also assumed that the safe yield of the basin to be protected was 30,000 acre-feet per year, if water levels could be safely maintained below sea level; but was decreased to 15,000 acre-feet if water levels must be raised to sea level or above as part of the plan for protection. This assumption is not applicable to the West Coast Basin, where safe yield would probably be negligible if water levels were maintained at sea level. However, in principle it more closely typifies general conditions in the areas of known sea-water intrusion.

Assumed water costs reflect conditions in the West Coast Basin. Softened Colorado River water at $23 per acre-foot was utilized for direct distribution; untreated Colorado River water at $12 per acre-foot was assumed for direct recharge of aquifers; and cost of the fresh-water barrier was based on reclaimed waste water at $10 per acre-foot. Estimated capital and annual operation and maintenance costs for a total usable supply of 80,000 acre-feet per year are presented in the following tabulation:

	Estimated costs for one-mile reach of coast	
Method of control	*Capital*	*Annual operation and maintenance, including water costs*
Reduction or rearrangement of pattern of pumping draft [a][b]	0	$136,000
Direct recharge of overdrawn aquifers [a]	$246,000	110,000
Fresh-water barrier [c]	210,000	86,000
Artificial subsurface barriers [b][c]	2,420,000	105,000
Pumping trough [b][c]	400,000	290,000

[a] Full utilization of ground water basin not possible. Assumed safe ground water yield 15,000 acre-feet per year.

[b] Assumes all major ground water producers have already connected to facilities from which they may obtain imported water.

[c] Assumed safe ground water yield 30,000 acre-feet per year.

CHAPTER V

EXPERIMENTAL STUDIES PERTINENT TO THE SEA-WATER INTRUSION PROBLEM

The more important prior experimental studies applicable to sea-water intrusion are discussed first in this chapter. Following this discussion, there is presented a summary of investigations conducted under Chapter 1500, Statutes of 1951, and other recent experimental studies. Part III of Appendix C to this report contains an abstract of literature concerning experimental studies directly concerned with sea-water intrusion.

PRIOR EXPERIMENTAL STUDIES

Many agencies have conducted experimental studies, varying in nature and scope, which are applicable to certain of the methods for control of sea-water intrusion set forth in the preceding chapter. Such studies have dealt principally with direct recharge of overdrawn aquifers through use of injection wells or through surface spreading, determination of parameters of sea-water intrusion, and reduction in aquifer permeability. Information of actual field experiments relating to the pumping trough method of preventing sea-water intrusion has not been found. Although much of the early work described in the literature consisted of individual studies or projects designed to correct some specific conditions and did not reflect a true experimental approach, it did provide valuable data to serve as the basis for succeeding studies.

Prior experimental studies discussed herein are grouped in five categories:

1. Parameters Governing Intrusion of Saline Water;
2. Recharge of Ground Water Through Injection Wells;
3. Recharge of Ground Water Through Surface Spreading;
4. Artificial Subsurface Barriers Through Grouting; and
5. Artificial Subsurface Barriers Through Construction of Earthen Walls.

Parameters Governing Intrusion of Saline Waters

A multitude of studies has been conducted to determine the nature and occurrence of sea-water intrusion, particularly with reference to the shape and rate of movement of the interface between the advancing sea water and the displaced fresh water. Such investigations have provided much valuable data needed for the development or application of the methods of sea-water intrusion control outlined previously.

European Studies. Sea-water intrusion into coastal ground water basins in England, France, Belgium, Germany, and the Netherlands has been observed and studied for many years. One of the first references to sea-water intrusion in the literature concerns infiltration of salt water into wells at London and Liverpool in England in 1855. Later literature describes high salinity concentrations in water from wells located along the coast of Hampshire, England in 1910. It was concluded at that time that heavy pumping was the cause of the observed intrusion. In 1916, Whitaker discussed, at some length, mixtures of native ground water and sea water found near Essex, England.[14]

d'Andrimont completed extensive studies on the availability, movement, and quality of ground water in the dune area along the Belgian coast in the early 1900's.[15, 16, 17, 18]

Both Dubois and Pennink investigated sea-water intrusion in the lowlands of Holland in 1905, noting that salinity of ground water appeared to increase with depth and pumping effected an increase in salinity.[19, 20] Both investigators corroborated the Ghyben-Herzberg principle previously discussed.

Reportedly, the fresh water content of the fresh ground water lenses in the Netherlands dunes is decreasing rapidly through overdevelopment. Thiele reported in 1953 that sea-water intrusion existed from Calais, France to Denmark, and added that the most carefully studied dune water lenses in the world were those at Amsterdam in the Netherlands.[21] The dune water lense at Leyden is being replenished through artificial recharge. The Government Institute for Water Supply at the Hague has estimated water requirements up to the year 2000 and the percentage of supply from dune water lenses, ground water from inland areas, and surface water sources. It is proposed that surface sources will be further developed and will provide a much greater percentage of the total water supply in the future. In the western portion of the Netherlands, 44 per cent of the total supply was obtained from dune water lenses in 1953, and it is estimated that in the year 2000 this value will have decreased to 13 per cent of the total supply.

Degradation of Ground Water Quality at Nassau, Bahama Islands. In 1933, Riddel reported on presence of saline waters in aquifers at Nassau on New Providence Island, Bahama Islands.(22) It was noted that salt water cones formed in aquifers below pumping wells; and that a series of wells of small capacities were more desirable than fewer wells of large capacities and drawdowns for the skimming of fresh water off the underlying salt water. This condition is similar to that found on many other islands.

Studies in Japan. Toyohara reported on a field experiment at Tottori, Japan, in 1935, which corroborated prior model sea-water intrusion studies, although some deviation from the theoretical was observed regarding diffusion along the salt water-fresh water interface.(23)

A report published in 1939 by K. Kitagawa presented derivations for the parabolic equations defining the fresh water-salt water interface and demonstrated that these equations compared favorably with results of model studies.(24) The report also described a field experiment utilizing observation wells and dyes to verify the shape of the interface.

A major earthquake occurring in Japan on December 21, 1947, resulted in substantial land subsidence and inundation of coastal areas. Salt-water infiltration into ground water supplies occurred, and the rate of advance and shape of the interface along the coast of the Island of Shikoku was observed. In 1951, Hayami reported on the field studies and developed a mathematical theory for the process of infiltration.(25)

Investigations in the Hawaiian and Other Pacific Islands. The United States Geological Survey studied sea-water intrusion in the Hawaiian Islands in the 1900's.(26) Studies in these islands in the 1930's confirmed the Ghyben-Herzberg principle and included determinations of depths to sea water by resistivity measurements using the Lee partitioning method.(27) Wentworth, in 1939, utilized the Ghyben-Herzberg principle to determine effects of various ground water and sea water specific gravities on the interface. He also reported on the relations between water temperatures and specific gravities.(28)

Application of the Ghyben-Herzberg principle to ground water conditions in the Hawaiian and Marianas Islands was reported by Ohrt in 1947.(29) Ohrt concluded that water supplies of the Pacific Islands were very limited and could best be utilized through use of skimming tunnels.

Ground Water Quality Studies in Connecticut. Shape of the salt water-fresh water interface was observed by the United States Geological Survey in Connecticut in the 1920's by sampling ground water at varying depths and distances from the shoreline.(30) The zone of diffusion at the interface was reportedly 60 to 100 feet in width. Relationships between pumping and ground water salinity, and yearly temperature and salinity were established.

Sea-Water Encroachment in Galveston-Houston Area, Texas. Studies conducted in the 1930's in the Galveston-Houston area, Texas, indicated that sea-water intrusion had occurred about 20 miles inland.(31) Abandonment of wells in Galveston in 1896 indicates that intrusion may have existed at that time. Ground water levels are now reported to be as much as 220 feet below sea level in Houston, and land subsidence in excess of three feet has been observed in this area.

Degradation of Ground Water Quality Near Parlin, New Jersey. In 1940, Barksdale reported that sea water in the pressure aquifer near Parlin, New Jersey, was advancing inland at a rate of approximately one mile in six years.(32) Observations in monitoring wells revealed that sea water advanced in waves of high salinity followed by waves of lower salinity, with each successive crest being higher than the previous crest.

Investigations Conducted in Florida. Sea-water intrusion has been a paramount problem in certain areas in Florida for the past 30 years. It has been determined that drainage canals have lowered the fresh ground water level in coastal aquifers, permitting intrusion of sea water in certain areas. Sea water has also entered these canals during dry periods, percolating into fresh water aquifers. The diffusion zone at the fresh water-salt water interface is about 60 feet wide.

Special investigations sponsored by the United States Geological Survey and the Florida State Geological Survey were begun at several locations about 1930. Alarming increases, in 1939, in chloride ion concentration of ground water at the well field serving the City of Miami, led to the initiation of intensive investigations into the occurrence and movement of sea-water intrusion in the area. It was found that intrusion had taken place over a 47-year period, with a rate of encroachment until about 1943 of approximately 235 feet per year.(33) During the drought of 1943-46, the rate increased to about 890 feet per year. As a remedial measure, low-level removable dams were installed in many of the numerous drainage canals. These dams, together with increased precipitation during the period 1946 to 1951, caused a seaward movement of the salt water front.

Members of the staff of the University of Florida prepared a report in 1953 for the Division of Water Survey and Research, State Board of Conservation, State of Florida, in connection with sea-water intrusion.(34) It was concluded from this investigation that the chloride ion is the most reliable indicator of sea-water intrusion, since this ion is not commonly subject to oxidation, reduction, or base exchange. Furthermore, although connate brines are also high in chloride ion concentration, sea water may usually be assumed to be the cause of degradation if a landward hydraulic gradient exists.

In reporting on the results of his studies in the Miami area, Love of the United States Geological Survey stated that when cation exchange occurred as a result of the movement of sea water through aquifers containing exchangeable materials, active colloids in the formation gave up calcium ions in exchange for the magnesium and sodium ions in the sea water.[35] In this regard, Revelle has indicated three types of modification which sea water may undergo in flowing through porous media; base exchange, changes in proportion of negatively charged ions as a result of sulfate reduction and substitution of acid radicals, and changes in both cations and anions through processes of solution and precipitation.[36] Love and Revelle agree that the chloride ion is the best indicator of sea-water intrusion, although Revelle recommends that a ratio of chloride to bicarbonate be used to eliminate the effect of a temporary increase in total dissolved solids.

Investigations of the Occurrence and Movement of Sea-Water Intrusion in California. In 1940, it was reported that degradation of ground waters was occurring in the Santa Clara Valley bordering the southern tip of San Francisco Bay; and it was found that sea water entering the aquifers through abandoned wells in tidal areas was the paramount cause of degradation.[37]

Studies by the State Division of Water Resources in the Salinas area revealed that in October, 1945, there were approximately 6,000 acres underlain with sea water, extending up to one and three-quarters miles inland from the coast.[38] The advance of the saline front was estimated at 600 feet from August, 1944, to August, 1945. Since a pumping trough existed in this basin, the advance of the saline front would be a maximum at the trough; and, at this point, would underlie approximately 9,200 acres.

The State Division of Water Resources, as Referee in an action to adjudicate water rights in the West Coast Basin, Los Angeles County, conducted an investigation from the fall of 1946 through the winter of 1950-51, including determination of areas underlain with saline water and the source of this water.[39] Sea-water intrusion in this area has been previously discussed in this report in some detail.

Starting in 1949, the United States Geological Survey, in cooperation with the Orange County Flood Control District and the Orange County Water District, undertook a field investigation of sea-water intrusion in Orange County.[40] The study included collection of water samples at various depths in key observation wells, making conductivity traverses within wells, determination of depths to ground water, collection of well logs, and ascertaining the transmissibility of underlying aquifers. Ground water samples were analyzed for chloride ion concentration, hardness and conductivity. This program included observation of the advance or recession of the sea-water front and the determination of the shape, rate of movement, and salinity changes in the front.

The State Division of Water Resources, in cooperation with Ventura County, conducted a water resources investigation in Ventura County in 1951-1953, which included determination of extent and source of high chloride concentrations near Port Hueneme.[41] A detailed discussion of this problem has already been presented in this report.

Recharge of Ground Water Through Injection Wells

The main water-bearing sediments within the major ground water basins along the coast of California are overlain with impervious deposits. This physical condition, coupled with high costs of rights of way, makes it generally infeasible to employ surface spreading techniques to raise piezometric surfaces above sea level in many overdrawn basins, and has led to experiments involving the use of recharge or injection wells to replenish ground water supplies.

The disposal of oil field brines through use of injection wells has been practiced in the petroleum industry for many years. Injection wells have also been extensively used to recharge ground water aquifers with cool water during winter months; and, during summer months, to return used cooling water to the aquifer from which it was withdrawn. Conservation and disposal of runoff and waste waters have also been important uses of injection wells.

Replenishment of Ground Water Supply at Long Island, New York. For many years, overdevelopment of ground water resources in the heavily urbanized and industrialized areas of western Long Island, New York, resulted in a gradual lowering of ground water levels; and in 1933 it was found that levels underlying more than 40 square miles in Brooklyn were below sea level.[42] Ground water levels reportedly reached their lowest stage in 1941, and in 1947 the last municipal well field in Brooklyn was abandoned as a result of sea-water intrusion. Since then, levels have recovered slowly, although they are still below sea level in many places.

Declining ground water levels prompted the passage of state legislation which provides that no well having a capacity in excess of 45 gallons per minute shall be drilled without prior approval of the State Water, Power, and Control Commission.[43] Since enactment of this legislation, the Commission has required that water pumped from new wells and used for cooling and air-conditioning be returned to the aquifer from which it was withdrawn in an unpolluted condition.

In 1954, approximately 715 recharge wells were used to return over 40 million gallons per day to aquifers underlying Long Island. Some recharge wells on Long Island, with capacities of more than 1,000 gallons per minute, have been successfully operated for as long as ten years without rehabilitation.

Approximately 75 per cent of the injection wells constructed on Long Island are screened below the phreatic line; and this type of well, when gravel-packed, appears to be the most suitable for this area. Although more expensive, due to greater depth, this type of construction, known as the "wet" type, minimizes clogging of the well screen by gases released from solution or air mixed with recharging water in the zone of aeration. Furthermore, standard methods of well redevelopement, such as surging, bailing, and chemical treatment, are not as applicable to the "dry" type injection wells which are screened above the zone of saturation.

According to Sanford, the most suitable type of injection well on Long Island is a 30-inch diameter pit with an 8-inch to 12-inch diameter inner casing equipped with an acid-resistant well screen.[44] Sanford also reports that the use of dry ice for well rehabilitation has proved both successful and economical. Hydrochloric and sulphuric acids may have to be used, in some cases, for loosening encrustations.

The temperature of water returned to the ground water supply through injection wells on Long Island ranges from 2 to 20 degrees higher than the temperature of water pumped from supply wells, depending on the type of industrial cooling apparatus. Although, at some installations, the temperature of the ground water has risen as a result of the return of warm water, the problem may be remedied by proper spacing of injection wells. Also it has been observed that the temperature of the ground water drops rapidly upon cessation of warm water injection.

It has also been demonstrated on Long Island, that properly treated industrial waste water, sanitary sewage, and storm runoff can be used for recharging. Storm runoff recharge wells in Nassau County, Long Island, usually consist of reinforced concrete slotted pipe sections $7\frac{1}{2}$ feet or 10 feet in diameter. The larger sections have 7-inch thick walls for depths down to 60 feet and 10-inch walls for greater depths. Sections are fastened together in six places through the slotted openings with vertical steel straps. Double straps are used for depths exceeding 60 feet. The end of the bottom section is open to aid recharge and is equipped with a steel cutting edge to facilitate sinking the well by the open caisson method of excavation.

Tests indicate that well infiltration rates as high as 440 gallons per square foot of seepage area per day can be expected with this type of well. It is reported that the most effective wells are those which extend more than six feet below the highest ground water level.

Water from storm drains passes through special catch basins before discharging into the recharge wells, permitting the heavier sediments to settle and deposit in the basin. Periodic removal of silt from catch basins and from the wells themselves is necessary to maintain satisfactory recharge rates.

Injection Through a Brackish Water Well at Camp Perry, Virginia. Injection and pumping experiments were performed in 1946 at Camp Perry near Williamsburg, Virginia, in a well which originally produced water with a chloride ion concentration of 340 parts per million.[45] Fresh water from the municipal distribution system was injected through the well for about 43 days, commencing at a rate of 250,-000 gallons per day and terminating at a rate of 200,000 gallons per day. When it became evident that the well was partially clogged, it was pumped and the discharge water analyzed.

These experiments indicated: (1) about 50 per cent of the amount of water recharged was not degraded when pumped from the aquifer; (2) some clogging of the recharge well could be expected, except where the water-bearing formation is coarse grained and the well highly developed when constructed; (3) foreign matter should be removed from the recharge water; (4) restoration of recharge rates is difficult; and (5) an observation well located near the injection well is desirable to indicate shape and extent of recharge mound.

Management of Ground Water Supplies at Louisville, Kentucky and Binghamton, New York. Industrial use of ground water in excess of replenishment occasioned an alarming lowering of ground water levels underlying Louisville, Kentucky, and resulted in one of the first planned operations of a ground water reservoir.[46] During the winter of 1944, industries united to carry out a program of using the municipal water supply consisting of filtered river water, rather than ground water, while injecting cold filtered river water through wells. The objectives of the operation were to raise ground water levels and keep the ground water temperature below 60° F during the ensuing summer. Recharge was continued for three months in the spring of 1944, using three wells at an average total recharge rate of 1,000 gallons per minute. Reports indicate that the project was successful.

A similar problem involving rapidly declining ground water levels in an industrial area in Binghamton, New York, was remedied by winter injection of cold water, pumped from wells near the Susquehanna River, through wells located at the cone of pumping depression.[42]

Deep Aquifer Replenishment at Canton, Ohio. In many coastal ground water basins, waters of only one of several producing aquifers may be degraded by sea-water intrusion. Injection wells can be utilized to convey water of good quality from one aquifer to a deeper aquifer into which sea water has intruded. The phenomenon of inter-aquifer flow using injection wells has been demonstrated in the Canton, Ohio, region, where a relatively thin aquifer overlies an aquifer of considerable storage capacity, the two being separated by an impervious member.[42] Three horizontal collector wells were sunk along streams which cross the area and recharge the upper aquifer. These collectors have continuity with both aquifers and allow water to flow continuously from the upper to the lower aquifer, the combined rate of recharge of the three collectors being about eight million gallons per day. One of the collectors is used as a source of supply; and about ten million gallons per day are pumped from the lower aquifer.

Artificial Recharge Experiments at El Paso, Texas. Excessive withdrawals from the ground water supplies underlying El Paso, Texas, resulted in an alarming drop in ground water levels, followed by the intrusion of saline waters. Recognizing the need for corrective measures, the City of El Paso, in 1947, requested the United States Geological Survey to study the feasibility of storing treated surface water from the Rio Grande in the ground water reservoir underlying the City.[47] During the winter months from 1947 through 1951-52, with the exception of the winter of 1949-50, water diverted from the Rio Grande and treated at the City's treatment plant was injected through a municipal well. Treatment consisted of screening, grit removal, prechlorination, aeration with forced air, primary settling, coagulation with alum or ferric sulfate, softening with lime, activated carbon treatment for taste and odor, settling, reflocculation, recarbonation, chlorination, and rapid sand filtration. The injection well was a city supply well drilled in 1924, and was in intermittent operation until injection was commenced. At first, recharging was accomplished through the pump conductor pipe; but later, after the pump was removed, injection was carried on through an injection pipe with gate valve. Bottoms of both pipes were about 100 feet below static ground water level.

It was concluded from this field investigation that intrusion of salt water could probably be retarded, and in some places even halted by injection of treated surface water at a rate of about six million gallons per day, utilizing three or four wells spaced 1,500 feet apart.

Injection Well Experiments by Los Angeles County Flood Control District in 1950. From May 16, 1950 through October 13, 1950, the Los Angeles County Flood Control District injected 325 acre-feet of water through a single well at Manhattan Beach, California, at rates varying from 0.5 second-foot to 2.3 second-feet. Water injected was a mixture of treated Colorado River water and native ground water from inland of the area of sea-water encroachment. The District's final report describing the experiment included the following conclusions:[48]

1. "The abandoned well used for recharge purposes in a pressure aquifer of limited thickness was able to convey flow to the ground water body for a 5-month period at rates between 1 and 2 cfs. Since this recharge was not chlorinated during the major part of this period, it seems conservative to assume that thoroughly developed new recharge wells can absorb at least 2 cfs of chlorinated water initially and 1 cfs over a considerable period of months without redevelopment."

2. "Bacterial slimes will form and clog the aquifers being recharged unless the flow is sterilized."

3. "With conditions as they exist at Manhattan Beach, it appears reasonable to expect that bacterial slimes can be controlled by dosing the recharge flow with chlorine at an initial dosage of 15 ppm."

4. "Chlorine dosages should be commenced immediately upon recharging in order to sterilize potential bacterial growth sources in the ground water around the well and prevent any build-up of bacterial slimes."

5. "The threat of clogging the aquifer by incrustations of insoluble carbonates did not occur to a noticeable degree during the duration of this test."

6. "It is desirable to exclude air from the recharge flow."

7. "The recharge flow displaced the existing saline water up to a radius of over 500 feet from the injection well. Pumping tests indicated that little or no mixing had taken place between the injected fresh water body and the displaced saline water."

The Los Angeles County Flood Control District conducted basin recharge experiments in the City of Los Angeles, north of the City of El Segundo, concurrently with the previously mentioned injection well studies at Manhattan Beach.[48] Initial basin recharging rates were quite low at the El Segundo test site due to the presence of relatively impervious, iron-cemented sand layers at depths of 12 to 20 feet below ground surface. To penetrate these semi-impervious sediments, 25 pit-type injection wells, 30 inches in diameter, and varying in depth from 23 to 46 feet, were drilled in the recharge basin at intervals of 40 feet and filled with pea gravel. The average injection rate per well after nine days of operation was 0.11 second-foot.

It was found advisable to maintain a mound of gravel at the top of each well to serve as a filter. These mounds were sterilized intermittently with copper sulfate or calcium hypochlorite to prevent clogging of the well with algae and bacterial slimes.

Injecting Reclaimed Sewage into Ground Water Aquifers in West Coast Basin, California. In July, 1946, Harold Conkling, Consulting Engineer, proposed that reclaimed sewage from the City of Los Angeles' sewerage system be injected into the ground water reservoir underlying the West Coast Basin in Los Angeles County.[49] Sewage would be aerated, filtered, and chlorinated prior to injection through 400-foot deep, 16-inch diameter cased wells, spaced not less than 2,000 feet apart. Injection wells would be so located as to maintain a minimum distance of 1,000 feet from pumping wells. Although injection rates over an extended period of time were estimated at about two second-feet, it was assumed that due to intermittent use a continuous recharge rate in the order of one second-foot per well would be more practicable. With injection wells in operation at this design rate, approximately 80,000 acre-feet of water per year would be added to the overdrawn aquifer.

This proposed replenishment program using injection wells and treated sewage has not been put into effect as yet, except on a field experimental basis as discussed later herein. Most of the area in the West Coast Basin has acquired rights to the use of imported Colorado River water by annexation to The Metropolitan Water District of Southern California.

Investigation of Travel of Pollution, University of California. From April, 1951, through 1954, the University of California at Berkeley, under contract with the State Water Pollution Control Board, investigated the travel of pollution in ground water within a shallow pressure aquifer at the University's Richmond Sanitary Engineering Research Field Station.[50] A portion of these studies was conducted concurrently with experimental investigations authorized by the State Legislature under Chapter 1500, Statutes of 1951, which are discussed hereinafter.

The field facilities consisted of one 12-inch injection well and eighteen 6-inch observation wells located at distances from 10 to 500 feet from the injection well. Diluted sewage containing coliform organisms in the order of 10^6 per 100 milliliters, suspended solids of 3.3 parts per million, and a BOD of 4 parts per million was injected at the rate of 31.6 gallons per minute.

It was concluded from the University's studies that coliform bacteria quickly reached an apparent maximum distance of travel with no increase in concentration resulting from additional injection. Coliform organisms decreased in number from 10^6 to less than 38 organisms per 100 milliliters while traveling 100 feet in 33 hours.

It was found that injection wells should be gravel-packed to obtain desirable injection rates. In addition, grouting was required above the aquifer to prevent injected water moving upward along the outside of the casing and eroding the overlying formation, causing subsidence around the well. These findings were corroborated by the injection well studies in the West Coast Basin, which are discussed at length in succeeding portions of this report.

As a result of the University's studies, it was also concluded that:

1. Serious clogging can result from the dispersion of the clay fraction of an aquifer, or of clay in the boundary layers of the aquifer, if excess sodium is introduced.
2. Clogging of an aquifer is directly proportional to the amount of solids injected in any period of time. With 20 and 27 per cent sewage, clogging produced an average rate of pressure increase in the recharge well of 5.5 feet of water per day.
3. Particulate organic matter does not penetrate the aquifer to any important extent. With the exception of bacteria and similar small particles, it tends to remain in a filter mat at or near the aquifer face.
4. The buildup of clogging during sewage injection produces a pressure pattern in the recharge well which shows conclusively that biological decomposition of organic solids takes place underground and acts to lower the rate of clogging. A sharp break in the pressure curve takes place after two or three days, indicating that a biological equilibrium has been established.
5. Pumping at moderate discharge rates is inadequate to remove clogging to a satisfactory degree.
6. Gas binding of the aquifer occurred when the temperature of the recharge water was lower than the temperature of the ground water.
7. The recharge well can be successfully developed by injecting heavy doses of chlorine to break up the organic mat built up in the aquifer, allowing a contact period, then pumping at approximately 80 gallons per minute for periods up to four hours.
8. It was found that in general the chlorine should extend to the 13-foot observation wells, remain in contact for about half a day, and be sufficient in amount to show a slight residual in the well discharge at the beginning of pumping.
9. Loss of fine material during redevelopment does not seem to endanger the aquifer at the discharge rates (up to 80 gallons per minute) used in the investigation.
10. It was necessary to develop the recharge well once a week in order to make possible continued injection of 20 or 27 per cent sewage at 37 gallons per minute.
11. Redevelopment of the recharge well involved a maximum discharge of from four to five per cent of the volume of the injected water.
12. The problems of recharge well operation rather than the danger of pollution travel seem to be the critical factors in sewage reclamation by direct recharge.

Other Uses of Injection Wells. Use of injection wells to dispose of storm runoff or to circulate cooling waters is common practice in California. Injection wells in southern Alameda County, parts of Orange County, and in the City of Fresno, have been used for storm runoff disposal for many years. Injection wells are used to return cooling waters to underlying aquifers in portions of the Sacramento and San Joaquin Valleys, and in the Los Angeles area.

Although the disposal of waste waters by wells is known to have been practiced in California, there is a paucity of available data concerning such disposal, with the exception of the University of California's field experiment at Richmond. It is known that more than 175 wells have been used in the Orlando, Florida, area for sewage disposal and drainage.(51) Reportedly, a deep well current meter was used successfully in certain of these wells to determine the horizons at which these surface waters entered the underlying limestone formation.

Although most of the uses just described cannot be considered controlled experiments, nevertheless such long term operation does indicate that using injection wells to raise ground water levels above sea level along the margins of coastal ground water basins may be a feasible method for preventing sea-water encroachment.

Recharge of Ground Water Through Surface Spreading

Direct recharge of overdrawn aquifers to maintain ground water levels at or above sea level may also be achieved through surface spreading. Spreading of storm runoff and sewage effluent has been successfully practiced for decades in California and in other locations. Mitchelson reports that the first recorded attempt at conservation of water by spreading was carried out by the Denver Union Water Company in 1889.(52) He further reports that spreading on the Santiago Creek and Santa Ana River cones in Orange and San Bernardino Counties, respectively, was first undertaken in 1896 and 1900, respectively. In 1895, the conservation of floodwaters of San Antonio Creek by spreading was first attempted near the mouth of San Antonio Canyon in Los Angeles and San Bernardino Counties, an activity which has been continued to the present time. Over one and three quarter million acre-feet of water were reported to have been spread in California since the turn of the century.

The forebay areas of most coastal ground water basins afford an excellent natural facility for the direct recharge of depleted aquifers by surface spreading, due to the absence of overlying impermeable sediments and the availability, in most cases, of runoff from mountain and foothill areas. Spreading in the forebays may not be sufficient to raise ground water or pressure levels above sea level in the coastal segments, however, due to inadequate aquifer transmission capacities. As previously discussed in Chapter IV, it may be necessary to utilize several methods of control to stem sea-water intrusion in any particular area. Surface spreading in the forebay areas, coupled with the use of injection wells nearer the coast line, may be required.

Artificial Recharge Basins on Long Island, New York. Overdevelopment of ground water supplies and ensuing sea-water intrusion at Long Island, New York, have occasioned construction and operation of over 300 artificial recharge basins by Nassau County.(43) This program of spreading storm runoff was initiated in 1935, and is conducted in an area approximately 100 square miles in extent. Average infiltration rates of about three feet per day have been observed. Harrowing and weed removal in basins is performed semiannually.

Staff of the United States Geological Survey commenced intensive studies of infiltration and evaporation in the project area in May, 1949. Preliminary results of controlled recharge in a 40-foot by 50-foot test basin indicate infiltration rates equal to, or greater than rates experienced at larger basins operated by the County.

Los Angeles County Flood Control District Experiments Near Redondo Beach. In conjunction with their previously described single well injection test at Manhattan Beach and injection pit test north of El Segundo, the Los Angeles County Flood Control District performed a surface spreading experiment in the sand dune deposits along the coast at Redondo Beach in 1950.(48) Major project facilities consisted of a one-acre basin and 23 observation wells. It was found that for the deposits in the area, percolation rates of from 2 to 3 second-feet per wetted acre could be maintained if the recharge water was chlorinated with dosage of about 3 parts per million to prevent growth of soil clogging micro-organisms.

Sewage Spreading Experiments by Los Angeles County Flood Control District at Whittier and Azusa. The Los Angeles County Flood Control District, in exploring the possibilities of large-scale reclamation of sewage, established and operated experimental spreading plots at the Whittier and Azusa sewage treatment plants.(53) Experiments were conducted with the effluents from these plants, under various degrees of treatment, to determine their percolation characteristics and the influence thereon of physical, chemical, and biological factors.

It was found that effluents from these plants, both of which use the trickling filter process, can be utilized to replenish ground waters by surface spreading. Sustained percolation rates ranging from 0.2 cfs per acre to 0.6 cfs per acre were obtained. The maintenance of aerobic environment in the spreading plot was essential. Satisfactory sanitary conditions resulted if the dissolved oxygen content of the percolating fluid was at least 0.5 ppm, and the biochemical oxygen demand less than 0.5 ppm. Comparison of sewage effluent with the originating water supply showed that the use cycle resulted in an increase of 172 ppm in dissolved solids content.

University of California Sewage Reclamation Field Studies at Lodi. In 1950, the Sanitary Engineering Research Laboratory, University of California, initiated a field investigation of sewage reclamation by surface spreading at Lodi, California, under the sponsorship of the California State Health Department, and later, the California State Water Pollution Control Board.[54] During the 28-month study, extensive chemical and bacteriological determinations were made which indicated that sewage could be reclaimed by spreading on Hanford fine sandy loam soil, at rates of about 0.5 foot per day, producing bacteriologically safe water if the liquid percolated through at least four feet of soil. It was further concluded that high infiltration rates are possible if a highly treated effluent is used.

Studies of sewage recharge were resumed at the University's Richmond Sanitary Engineering Research Field Station in 1952, with one of the objectives being the determination, using lysimeters, of infiltration rates of five typical pervious California soils. Application of settled sewage produced abrupt decreases in infiltration rates for the more permeable Oakley and Yolo soils, while little or no change was noted for the less permeable Hanford, Hesperia, and Columbia soils. After 48 hours of application, infiltration rates for Oakley and Yolo soils dropped from 30 feet per day and 15 feet per day, respectively, to 0.5 foot per day and 2.0 feet per day, respectively. Infiltration rates for Hanford, Hesperia, and Columbia soils remained fairly constant at 0.8, 0.6, and 0.6 foot per day, respectively. The marked decline in rates for the more permeable soils was attributed to clogging of the soil surface by particulate matter.

Artificial Subsurface Barriers by Grouting

As previously discussed, reduction of aquifer permeability may be the most feasible method of controlling sea-water intrusion into certain coastal basins. Reduction in permeability may be accomplished in various ways depending upon physical conditions, such as depth of aquifer below ground surface and particle size of sediments. Artificial subsurface barriers have been constructed by grouting with cement, chemicals, silts and clays, or asphalts, or installation of an earthen cutoff wall.

Cement Slurries. Laboratory studies to develop suitable grouting materials have been myriad in number, especially those dealing with cement. Cement slurries have been used in oil well drilling and to seal rock fractures and porous materials underlying structures, notably dams, for many years. Techniques regarding grouting mixes, additives, and operating pressures have been developed to a high degree. Although cement grouting has proven successful in sealing coarse-grained materials, cement particle size prohibits effective sealing in materials finer than fine sand.

Intrusion-Prepakt, Incorporated, reports they have achieved complete water shut-off at depths up to 60 feet by use of a process called mixed-in-place intrusion grouting. This process consists of injecting cement grout through a hollow shaft to a rotating mixing head, which mixes the slurry with the soil in place.[55] The result is a pile-like column which, in combination with adjacent columns, provides a cutoff wall.

Chemical Injection. In recent years, consideration has been given to injection of chemicals for reduction of sediment permeability. Bentonite, chromelignin, calcium acrylate, and a silica gel combination of sodium silicate and calcium chloride have been particularly studied as grouting media. Aniline furfural used with vibrators, sodium and calcium ion exchange, dissolution of silica with acid, and pore water freezing by use of carbon dioxide are other techniques considered.

Of all the chemicals, a mixture of sodium silicate and calcium chloride has probably been the most commonly used, being successfully employed to stop seepage and prevent movement of quicksand. The first use of sodium silicate and calcium chloride was reported in Europe, and it is known that many technical papers have been written, especially in France, Germany, and Russia, concerning studies of its use. In 1929, a modification of this method was utilized in rendering watertight the cutoff wall for Alexander Dam at Kauai Island, Hawaiian Islands, by use of a mixture of soda ash, or crude sodium carbonate, and clay soil containing silica.[56]

Charles Langer, a French engineer, has reportedly developed a technique for controlling reaction time between sodium silicate and calcium chloride by lowering the pH of ground water through addition of acid to the mixture.[57] By delaying the time of set, greater penetrating distances can be realized.

Laboratory studies by Polivka at University of California at Berkeley indicated that, due to the low viscosity of the silicates, a mixture of sodium silicate and calcium carbonate could be injected into formations where other materials, such as cement, bitumen or bentonite, might fail to penetrate.[58] However, in this regard, it has been reported that for chemicals with the viscosity of water, injection into clay soils is for all practical purposes impossible, and injection into silts is possible only with high pressures.[59]

The United States Bureau of Reclamation reports that solutions of sodium silicate, in combination with calcium chloride, sodium bicarbonate, or aluminum sulfate, penetrated tight rock seams better than did cement grout.[60] This was attributed to the fact that these chemicals formed a colloid. The Bureau of Reclamation has employed two methods of chemical grouting: (1) single injection method in which the chemicals are mixed before being pumped; and (2) double injection method in which the individual chemicals are pumped separately into the formation.

Riedel has described a chemical process which solidified sediments and improved the foundation under a bridge pier near Kuttawa, Kentucky.[61] Loose soft rock, sand boils, and artesian water were encountered during construction of the bridge pier. Sodium silicate and calcium chloride were pumped alternately into the formation through pipes until water and sand boils were sealed satisfactorily. Subsequent tests indicated that the chemicals had formed a soft sandstone which was impervious to water and exhibited bearing strengths up to 50 tons per square foot. Also, it was found that this process is not applicable to strata containing more than 25 per cent clay, silt, or sand passing a 125 mesh sieve.

Sodium silicate and calcium chloride solutions were also used to successfully seal leaks at an underpass at La Grande, Oregon.[62] Solidification of strata to depths of approximately one foot beneath the concrete base of the underpass was achieved by pumping the solutions at 400 pounds per square inch pressure through a series of one and one-half inch holes.

According to some recent research by T. W. Lambe, calcium acrylate is the best soil solidifier.[63] These tests included determinations of volume change, strength, and flexibility.

Solutions of stabilizer AM-955, acrylamid methylenebisacrylamide, either alone, or mixed with calcium acrylate with suitable catalysts, have been used to stabilize and reduce the permeability of cohesionless sands.[59] Compressive strength of one type of sand, after polymerization of AM-955, was about 20 pounds per square inch, permitting vertical cut excavation in the treated sand.

Intrusion-Prepakt, Incorporated, in cooperation with Hough Soils Engineering Laboratories, conducted a grouting experiment near Wyoming, New York, using chrome-lignin.[64] Conclusions drawn from the experiment are as follows:

1. Chemical grout, like cement grout, follows the paths of least resistance through the soil;

2. Underground chemical flow rates can be immediately altered by varying the slurry viscosity;

3. Chemical grout can be pumped with approximately one-sixth the pressure required to pump cement grout, under like conditions;

4. Chemical grout can be pumped through any material through which water can be pumped;

5. Surface "break-outs" are more prevalent with chemical grout than with cement grout.

Plastics have also been used to reduce aquifer permeability. In oil well drilling in Texas, nearly 83 per cent of the sealing attempts using plastics resulted in over 50 per cent shut-off; and about 65 per cent of the attempts resulted in 100 per cent shut-off.[65] Liquid plastics proven to be suitable for oil well sealing are unpolymerized styrene, vinylidene chloride, partially condensed phenolformaldehyde, vinyl esters and ester of maleic acid with diethylene glycol. These plastics are all clear liquids, contain no suspended matter, and undergo polymerization, condensation, or association reactions until the whole liquid becomes an insoluble, strong, solid plastic when subject to temperatures encountered in oil wells.

Use of Silts and Clays. Silt and clay, especially bentonite, have been used for many years to reduce aquifer permeability. In 1926, Warren reported that bentonite does not absorb saturated salt solutions, and no volume change occurs when bentonite is in the presence of such solutions.[66] This finding, of course, is very pertinent as far as reducing ground water movement by grouting with bentonite which may come in contact with intruding saline waters. Warren further reports that bentonite in contact with pure water swells to several times its original volume.

Davis performed further work in connection with the swelling of bentonite in the presence of different liquids.[67] These studies indicated that lubricating oil, kerosene, and gasoline prevent bentonite swelling and leave a hard, granular residue. Saturated solutions of salts also prevent bentonite from swelling, although dilute solutions of salts merely retard swelling. While it was found that increasing the temperature accelerated the rate of swelling, an increase of acidity or akalinity decreased the swelling rate.

Experiments with bentonite by the United States Army, Corps of Engineers, in 1938, 1939, and 1940 were concerned with methods of mixing bentonite with water to form grout, stability of slag treated with various concentrations of bentonite grout, and the ratio of bentonite grain size to the grain size of the soil to be treated.[68, 69, 70]

In 1952, Johnson described a field project in Nebraska in which a slurry of graded loess, a yellowish clay or loam, was injected under pressures ranging from 80 to 270 pounds per square inch, into wells spaced 50 feet apart, to stop seepage from unlined canals.[71] The wells consisted of 6-inch diameter holes, 150 feet deep, equipped with 2-inch diameter pipes 40-feet long centered within the holes and surrounded by gravel envelopes. It was found that seepage could be halted for a distance of 80 feet from the well at a cost of about one dollar per cubic yard of injected slurry.

Asphalts. The use of cement, chemical, and clay grouts is often unsatisfactory in reducing aquifer permeability in areas of relatively high ground water velocities. In many such cases, desired results have been achieved by grouting with hot asphalt. For example, the United States Bureau of Reclamation has used asphalt to seal cavities or joints underlying and adjacent to hydraulic structures, where use of conventional grouting materials has proven unsuccessful.(60)

The United States Army, Corps of Engineers, in a report released in 1950, discussed an experimental field investigation at Mansfield Hollow, Connecticut, where pervious soils were grouted with asphalt emulsion.(72) Stratified sand and gravel deposits, a portion of which were below the phreatic line, were sealed to a depth of 35 feet through use of 10 injection holes spaced equally distant along the circumference of a 10-foot diameter circle and one hole at the center of the circle. The degree of sediment permeability was ascertained subsequent to grouting by pumping tests, sample borings, and open trench excavation; and it was found that seepage was markedly reduced where asphalt emulsion had penetrated. It was concluded, however, that the method of injection used did not result in a uniform distribution of asphalt due to the stratified formation.

Leakage of more than 450 second-feet from Great Falls Reservoir, Tennessee, was reduced to two per cent of this flow by injecting either cement or hot asphalt into 608 holes along a cutoff line almost a mile long.(73) Where leakage occurred at all reservoir elevations, asphalt was used; while cement grout was used where leakage occurred at high reservoir stages only. Five hundred-gallon capacity heaters and double-acting reciprocating pumps were employed for melting and placing the oxidized petroleum asphalt. With asphalt temperatures varying from 300° to 350° F., average pumping rates from 40 to 80 cubic feet per hour were attained at an average cost of $1.35 per cubic foot of asphalt, including materials and placement. Total cost of cement and placement was $1.19 per cubic foot of cement. Packers were used for both asphalt and cement grouting, with greatest penetration being achieved when packers were placed as close as possible to the cavities or pervious sediments.

Shell Development Company has evolved the "Shellperm" process in which Shellperm, a patented asphaltic emulsion, is pumped through pipes, placed at appropriate spacing and depth, into sediments to be solidified. Chemicals in the asphalt emulsion cause the asphalt to separate, coagulate, and form an impermeable plastic mass within the interstices of the deposits.

Shellperm was originally developed to improve foundation soils. It has been employed at numerous locations in the United States, as well as in Egypt, Belgium, Holland, and England. In 1948, Shell Development Company reported on a series of experiments to determine distribution of Shellperm in saturated, damp, and dry sands.(74) Results indicated that an emulsion containing 30 per cent by weight of asphalt could be successfully injected into the aforementioned types of sand if one per cent of casein stabilizer were added, pressures controlled to avoid channelization of asphalt flow, and ethyl formate, which is added to the emulsion to produce hardening, was first mixed with the diluting water to avoid lumps forming in the mixture.

The first large scale field test in the United States using Shellperm was undertaken in 1948 on the Santa Ana River, in Orange County, California, where a vertical cutoff wall was installed to prevent leakage at a diversion dam. Asphalt was injected in the amount of 10 gallons per vertical foot in holes spaced four feet apart along a 350-foot reach, and 20 gallons per vertical foot into a second line of holes, offset 1½ feet from the first line and staggered in relation thereto.(75) Depths of holes varied from 5 to 30 feet and pressures varied from 20 to 30 pounds per square inch. A total of 32,400 gallons of emulsion were used at this site, resulting in the conservation of approximately 0.88 acre-feet of water per day which ordinarily would pass beneath the diversion dam as underflow.(76) It was noted, however, that irregularities in the distribution of emulsion near ground surface resulted in incomplete impermeabilization.(77)

Shellperm was used to reduce ground water seepage 70 to 80 per cent at the Witherby Street Undercrossing in San Diego.(78) An emulsion containing 60 per cent by weight of asphalt was necessary.

It has been generally concluded from field experiments performed to date that grouting with asphalt emulsions effects appreciable reductions in soil permeability where uniform distribution of injected asphalt has been achieved. Although this condition is seldom realized, further development of asphalts and injecting techniques may increase the degree of impermeabilization.

Artificial Subsurface Barrier Through Construction of Earthen Wall

Other artificial subsurface barriers to ground water flow may take the form of earthen cutoff walls, which may be defined as artificial subsurface structures having definite physical boundaries and formed primarily of earthen materials which are relatively impermeable. Earthern core or cutoff walls have been constructed at hydraulic structures, principally dams, for many years, their construction consisting primarily of excavation of overburden and placement of imported, relatively impermeable fill. This excavated material itself may be backfilled and compacted after proper mixing with suitable sealing agents.

Construction techniques employed in the installation of cutoff walls vary with depth and degree of consolidation of formations encountered. In unconsolidated materials, a slurry similar to the mud used in oil well drilling is often used to: (1) support walls of the trench during construction; and (2) mix with, and thus decrease the permeability of the backfill.

Wilmington, California. One of the major earthen cutoff wall installations on the West Coast is located at Wilmington, California, where it became necessary to increase the width and height of levees surrounding the properties of the Union Pacific Railroad Company, Southern California Edison Company, and General Petroleum Corporation because of land subsidence. To prevent movement of sea water through and under the levees, over 18,000 lineal feet of three-foot wide, clay cutoff wall, ranging from 15 to 45 feet in depth below land surface, was installed by the Macco Corporation in 1950 on Union Pacific Railroad Company land.[79, 80] The trench for the cutoff wall was excavated with a rebuilt, Buckeye C-20, ladder-type, positive action ditching machine. Rotary drilling mud, containing bentonite, was pumped into the trench during construction. The slurry was displaced with dry, imported, selected clay, which was backfilled and tamped into the trench. This type of wall is termed a "puddled clay" cutoff wall.

The trencher, trucks containing mud, desander, and backfilling unit operated at specified distances apart along the ditch, and an average of 400 lineal feet of cutoff wall were installed per eight-hour day at an approximate cost of $2.50 per square foot of wall. Core samples were taken at 25-foot intervals, and it was found that the wall was free from sand lenses and voids.

To demonstrate the effectiveness of the installation in eliminating seepage, piezometer tubes were placed on the seaward and landward sides of the wall, and the landward side was dewatered using well points. Water levels observed regularly on the seaward side reflected tidal fluctuations, while water levels on the landward side showed no such fluctuations, indicating that a seal had been formed.

The contractor contended that, although the equipment used on that particular project could not go deeper than 45 feet, much greater depths could be attained if the volume of work was sufficient to justify the expense of developing and altering equipment.

Pasco, Washington. To prevent the flow of water from the reservoir formed by McNary Dam under the levees along the Columbia River, impervious cutoff walls were installed in the levees, with the walls extending down 30 to 60 feet to an underlying impermeable formation.[81] A clam shell was used to excavate the material from the 6-foot wide open trench, excavated material then being placed in windrows where it was blended with imported materials. Subsequent to mixing, a bulldozer pushed the material into the open ditch. The results of core drilling indicate that a greater impermeability was obtained than was required by the specifications.

The work was conducted by Peter Kiewit Sons Company of Longview, Washington, under the supervision of the United States Army, Corps of Engineers.

Kennewick, Washington. Approximately 10,580 lineal feet of cutoff wall, three times that installed at Pasco, were constructed at Kennewick, Washington, across the Columbia River from Pasco.[82, 83] Unsupported open trench excavation was attempted first, but proved difficult due to the unconsolidated nature of the subsurface materials and excessive ground water flows, which resulted in excessive amounts of excavation. The contractor, M. H. Hasler Construction Company and D. and H. Construction Company, then employed the Wyatt method, which utilizes a bentonite and water slurry to stabilize the ditch walls without caving. Slurry in the ditch was maintained at a sufficient level to balance the ground water head; and the viscosity of the slurry, plus a "filter cake" formed on the walls, prevented the slurry from flowing through the trench walls. The presence of four-foot boulders made it inadvisable to use a trencher, necessitating the use of Manitowoc 4500 and Lima 1201 draglines.

EXPERIMENTAL STUDIES UNDER CHAPTER 1500, STATUTES OF 1951

As previously mentioned, by enactment of Chapter 1500, Statutes of 1951, the State Legislature directed that an experimental program be undertaken to determine design criteria for the prevention and control of sea-water intrusion into ground water basins; and appropriated $750,000 to the State Water Resources Board for its implementation. To carry out the intent of this legislation, the State Water Resources Board requested the Division of Water Resources to outline such an experimental program, which was subsequently set forth in the Division's report entitled "Proposed Investigational Work for Control and Prevention of Sea-Water Intrusion Into Ground Water Basins," dated August, 1951.

The following four sea-water intrusion investigations were performed with the funds indicated and are discussed hereinafter:

Investigation	*Contractor*	*Total allocation*
1. West Coast Basin Experimental Project	Los Angeles County Flood Control District	$642,126.30 *
2. Model studies, reduction in acquifer permeability and abstract of literature	University of California at Berkeley	$25,000.00
3. Permeability studies	University of California at Los Angeles	$10,000.00
4. Water quality investigations	United States Geological Survey, Quality of Water Branch	$10,000.00
Subtotal		$687,126.30
Supervision, inspection, coastal surveys, and reports	State Department of Water Resources (formerly Department of Public Works, Division of Water Resources)	$62,873.70
Total		$750,000.00

* See following section for itemized breakdown.

West Coast Basin Experimental Project, Los Angeles County

To implement the approved experimental program, the State Water Resources Board entered into a contract with the Los Angeles County Flood Control District on October 1, 1951, for prosecution of certain phases of the work. The Board made an initial allocation of $450,000 to the District for installation and one year's operation of a field experimental project in the vicinity of Manhattan Beach, Los Angeles County, to investigate the hydraulic feasibility of creating a pressure ridge in confined aquifers by means of injection wells, using fresh water, and the effectiveness of such a ridge in preventing sea-water intrusion. Amendments to this agreement extended the contract period to June 30, 1954, and included additional allocations, resulting in a total state allocation to the District of $642,126.30, which was expended as follows:

Item	*Cost*
Capital	$333,870.14
Operating and maintenance	98,833.53 *
Engineering, investigation and testing	109,705.33
Supervision	84,201.00
Miscellaneous	15,516.30
Total	$642,126.30

* Includes $32,967.80 for cost of recharge water.

These funds were exhausted in December, 1953, but the District has continued operation on a reduced scale, using its own and local funds. In 1954, project facilities were sold to the District except for certain engineering equipment which was retained by the Board. The Los Angeles County Flood Control District's final report describing the field experiment appears as Appendix B to this report.

Experimental Objectives. Under terms of the contract between the State Water Resources Board and Los Angeles County Flood Control District, the purpose of the field experiment was to determine, if possible, the following:

1. Feasible rates of injection through wells as related to thickness, permeability, and other properties of the aquifers, and variation in rates of injection with pressure head built up in the well and with time;
2. Height and shape of pressure ridge that can be built up as related to thickness and permeability of aquifer and hydraulic gradient;
3. Required height of pressure ridge and amounts of water necessary to inject to control intrusion of sea water as related to depth of aquifer;
4. Required spacing of injection wells to control sea-water intrusion as related to thickness of aquifer, permeability, and hydraulic gradient;
5. Gradient of the pre-recharge piezometric surface in the water-bearing deposits and its effect on the quantity of water injected and the shape of the pressure mound;
6. Rates and amounts of displacement of saline waters and/or degree of dilution of saline waters;
7. Effect of ground water extractions in the inland areas on the rate of injection necessary to control sea-water intrusion;
8. Degree of chlorination or other treatment necessary for continued injection of water at feasible rates;
9. Maintenance of wells, including procedures such as sand bailing, surging, deaeration, and studies of formation of microorganisms and the effect of chlorination or other methods of disinfection on their growth, and studies of base-exchange reactions and suspended solids deposition.

Description of Field Site. The site of the experimental field project is located within the boundaries of the Cities of Manhattan Beach and Hermosa Beach, as shown on Plate 21, and its selection was based on considerations enumerated below:

1. Sea water had intruded into the main aquifer underlying the area;
2. The Atchison, Topeka and Santa Fe Railway Company, which has a single track line approximately paralleling the coast line at a suitable distance inland, provided free right of way for project facilities;
3. A source of suitable injection water was available in the vicinity, namely, filtered and softened Colorado River water through facilities of the Metropolitan Water District of Southern California;
4. The underlying Silverado water-bearing zone is a confined pressure aquifer suitable for the desired experiments utilizing injection wells;

5. Existing piezometric surface and the Silverado water-bearing zone are comparatively close to ground surface in the area;
6. Local interests were desirous of reclaiming as much of the aquifer underlying the test site as possible.

Areal geologic features of the test site are depicted on Plate 22. As mentioned, this site is underlain at relatively shallow depths by the confined merged Silverado water-bearing zone in the San Pedro formation of Pleistocene age, as shown on Plate 23. This zone contains two phases; an upper brown phase and a lower gray phase. The upper brown phase is primarily a continental and littoral deposit, consisting of yellowish-brown gravel, sand, and silt. This phase grades into the lower gray phase, which is a shallow marine deposit, consisting of fine to very fine silty sand and clay. A study of the rock fragments indicates only minor differences between the two phases. The larger rock fragments are granitic types, with some metamorphics, volcanics and sedimentary types. Quartz and feldspar make up the major portion of the sediments in both phases. Mineral content of the upper phase ranges from about 1 to 15 per cent, and includes magnetite, ilmenite, pyroxenes, amphiboles, micas, and a number of other minerals. In the lower gray phase, the range of heavy minerals, consisting largely of biotite, is from about 2 to 8 per cent. Thickness of this formation is about 110 feet at the northern portion of the test area, increasing to over 150 feet at the southern end. The top of the zone is a few feet below sea level near the coast and dips landward so that near the recharge line it is approximately 30 feet below sea level. There appears to be a continuous clay cap overlying this formation, varying in thickness from about 20 feet near the inland boundary of the test area to mere traces at the beach. The lower limits of the Silverado water-bearing zone are bounded by relatively impermeable silts and clays of the San Pedro formation. As previously discussed, the productive Silverado zone is the coarse basal member of the San Pedro formation and is a distinct body of highly permeable sand and gravel with scattered discontinuous layers of relatively impermeable sandy silt, silt, and clay. Transmissibility of this zone, as determined by the Los Angeles County Flood Control District by field pumping tests along the recharge line varied from 32,300 to 161,600 gallons per day per foot (0.05-0.25 cfs/ft) and averaged about 106,600 gpd/ft (0.165 cfs/ft) prior to recharge.

Pressure levels, which were above sea level throughout the West Coast Basin in the early 1900's, had dropped below sea level at individual wells by 1920; and by 1932, levels were below sea level throughout most of the area. Since that time, the decline in pressure levels has continued with only minor interruptions, with the greatest lowering occurring northeast of Wilmington where a pumping trough has been formed. Pressure levels in this area were as much as 105 feet below sea level prior to the curtailment of pumping of ground water which commenced June 1, 1955, under agreement among the major water users. Pressure levels along the recharge line varied from about 5 to 12 feet below sea level prior to initiation of the experiment.

Concurrent with declining pressure levels has been the degradation of ground water quality along the coastal margin of the West Coast Basin. Chloride ion concentrations along the recharge line immediately prior to injection varied from 10,700 parts per million to 18,300 parts per million. Throughout the general area of the test site, within 6,500 feet of the coast line, the chloride ion concentration of the ground water exceeded the United States Public Health Service permissible maximum of 250 parts per million for domestic water.

Project Facilities. Construction commenced in January, 1952 with the initiation of well drilling, and was completed one year later. Nine 12-inch injection wells, one of which was gravel-packed, were drilled at 500-foot intervals along the Atchison, Topeka and Santa Fe Railway Company right of way, lying approximately parallel to, and some 2,000 feet inland from the coast line. Thirty-six 8-inch observation wells were drilled at selected locations surrounding the recharge line. The cable tool method of well drilling was employed since it was felt that this technique would result in more accurate logs, more suitable perforation locations, and more satisfactorily developed wells free of drilling mud. All of the aforementioned 45 wells were perforated in place using a Mills Knife, with the exception of the gravel-packed recharge well, which was perforated in place using a Moss Hydraulic Perforator. Double, hard red steel casing was installed throughout. All wells were very carefully logged; and samples and cores of formation material were taken for further study.

Construction of a steel pipe line and appurtenances, to convey treated and softened Colorado River water from the supply line of the Metropolitan Water District of Southern California to, and along the recharge line was started in the fall of 1952 and completed in February, 1953, when injection was initiated. The pipe line consists of approximately 10,000 feet of 20-inch, 10 gage pipe and approximately 2,000 feet of 14-inch and 16-inch, 12 gage pipe, all asphalt dipped. Installation of chlorination equipment completed the initial facilities.

As the field experiment proceeded, it became necessary to add eighteen 2-inch and four 4-inch observation wells and to replace two nongravel-packed recharge wells with gravel-packed wells. It also became necessary to cement grout several of the recharge wells when formation subsidence or leakage above the confining clay member became evident. Locations of project wells and pipe line are shown on Plate 21.

Project facilities included extensive instrumentation and metering in order to measure and record total and individual flow rates to injection wells, chlorine dosage, chlorine residual, fluctuations of pressure levels in 10 key observation wells, and conductivity of ground water in four strategic wells. Specially fabricated well header assemblies and back pressure valves prevented air entrainment during recharge operation.

Extensive tests and studies were conducted prior to initiation of recharge to determine hydraulic characteristics of injection wells, and hydraulic and geologic characteristics of the aquifer.

Recharge Operations. The first phase of the recharging program involved five of the recharge wells spaced 1,000 feet apart, with injection commencing in Well G, the center well. Artificial recharge was commenced in February, 1953, with injection through Well G at a rate of 0.5 second-foot. Pressure levels were affected in observation wells approximately 1,200 feet inland almost immediately; and under a constant recharge rate, stabilization was attained in approximately five days. As the injection rate was increased in this well, the two adjacent injection wells, located 1,000 feet distant north and south, were put into operation, with the injection rate in these wells being increased at planned intervals. It was planned to continue this operation with additional wells north and south of Well G being put into operation progressively. It was hoped that an injection rate of approximately one second-foot per well would be attained eight weeks after injection was initiated in Well G. Unfortunately, formation subsidence at Wells G and I and leakage of recharge water upward around the casing of Well C into the strata above the clay cap prevented the completion of this program. The necessity of decreasing well spacing, reducing individual well injection rates, and reducing injection heads within the injection wells was manifested by these difficulties. Injection was subsequently initiated in a total of eight recharge wells spaced 500 feet apart. Recharging in the ninth recharge well, Well C, was discontinued in May, 1953, due to the aforementioned upward leakage and was not resumed until June, 1955, after cement grouting.

Initial injection rate at all eight injection wells was approximately 0.5 second-foot; however, it soon became evident that an unbalanced pressure ridge developed under this uniform rate due to lateral flow at the ends of the injection line and variations in aquifer transmissibility. It was, therefore, decided to vary the individual well injection rates in such a manner as to obtain a ridge with pressure level elevations of about 2 to 3 feet above sea level at the internodal points midway between injection wells. These elevations were determined to be sufficient to halt the inland flow of sea water, in accordance with the Ghyben-Herzberg principle. Pressure levels along the recharge line between Well D and Well K were equal to, or above, 2.5 feet above sea level for the first time in January, 1954, with eight wells operating at a spacing of 500 feet. These levels have been maintained equal to, or above, the required elevation of 2 to 3 feet above sea level since that time, except for short periods during maintenance operations on wells or pipe line.

It was found that a total recharge rate of about 4.5 second-feet was required to maintain the ridge along the 4,000-foot test reach, or about 6 second-feet per mile. Injection rates along the recharge line varied from about 0.3 second-foot to 1.1 second-feet per well. With the view of determining the maximum acceptance rate of gravel-packed Well E, the injection rate through this well was increased in small increments until a maximum rate of 1.86 second-feet was attained on May 12, 1954.

Injection heads required to maintain desired pressure-level elevations at the internodal points varied from 35 to 75 feet in June, 1954. Injection rates of over 1.0 second-foot were maintained with injection heads of from 27 to 50 feet in gravel-packed wells, while approximately the same heads were required to maintain one-half of this rate in nongravel-packed wells. Average recharge rate per foot of injection head was approximately 60 per cent of the average discharge rate per foot of drawdown observed when the recharge wells were pumped during development.

Lines of equal elevation of ground water before commencement of injection operations and after stabilization of the pressure ridge are shown on Plate 24. Pressure level profiles along and normal to the recharge line are shown on Plates 25 and 26, respectively.

Recharge Water Treatment. Concurrent with recharging operations, experiments were conducted to determine the minimum chlorine dosage for the recharge water, which had already been filtered and softened, to maintain suitable well acceptance rates. Recharge water was chlorinated at 20 parts per million at the commencement of injection in February, 1953. This dosage was subsequently reduced in small increments until the dosage was 1.5 parts per million in April, 1954. The district concluded that a chlorination rate of less than 10 parts per million and more than five parts per million was required at the test site to control the growth of slime-forming bacteria which tend to accumulate at the well perforations and at the face of the aquifer. In addition, a "shock" treatment of 20 or more parts per million of chlorine was occasionally required.

No redevelopment of injection wells was required during the test period except as a result of inadequate well construction. Hence, little knowledge was gained relative to the ultimate useful life of the wells and redevelopment needed to maintain effective well operation.

Occurrence and Movement of Saline Wedge. As previously mentioned, the chloride ion concentration of the ground water underlying the recharge line varied from 10,700 to 18,300 parts per million prior to initiation of recharge operations. The concentration decreased greatly with increased distance from Santa Monica Bay, with the 250 parts per million isochlor being approximately 4,200 feet inland from the recharge line and 6,500 feet from the coast. An intensive ground water sampling program was undertaken in the test area before and during operations, using "thiefs" and portable pumping equipment. Analyses of water samples collected at various depths in the observation wells indicated that salt water was intruding under the fresher native ground water in the form of a wedge. The toe of this wedge was located approximately 3,000 feet inland from the recharge line prior to injection, and a wedge of relatively fresh native ground water existed near the top of the Silverado water-bearing zone, overlying the saline wedge, in the region of the recharge line.

Injection of fresh water along the recharge line resulted in a "splitting" of this wedge and a flow of injected water and sea water both seaward and landward from the recharge line. Injected water tended to override and displace the intruded saline water with very little commingling exhibited. As recharging operations proceeded, injected fresh water completely displaced the saline water directly beneath the injection well line. During a 21-month period of recharge the "amputated" toe of the previous saline wedge moved inland approximately 2,000 feet while the remainder of the wedge moved seaward about 500 feet.

Chloride ion concentration in Well MB-8, located approximately 2,850 feet inland from the recharge line, increased from 1,500 parts per million in January, 1953, to over 5,400 parts per million in February, 1955. The chloride ion concentration in Well M-18, situated approximately 4,900 feet inland from the recharge line, increased from 390 parts per million in January, 1953, to 1,280 parts per million in August, 1955. The chloride ion concentrations of ground water at these two wells subsequently decreased with the passing inland of the saline wave and the arrival of the fresher injected water. It is of particular interest that, although there was apparently little commingling between the intruded sea water and injected fresh water, the highly saline water originally underlying the recharge line was never detected in inland observation wells.

Conductivity traverses in wells along the recharge line indicated that a considerable period of recharging is required to freshen the entire thickness of aquifer at the internodal points. This is primarily due to the existence of a stagnation point, or area of no ground water movement, in the flow net near the internodal point, produced as a result of the superimposition of the radial flow pattern from injection wells on the pre-recharge piezometric surface.

Lines of equal chloride ion concentration of ground water before recharging in June, 1955, are shown on Plate 27. The inland movement of the saline wave is illustrated on Plate 28, and changes in chloride ion concentrations in key wells are shown on Plate 29.

Computations by Mr. J. A. Harder of the University of California, Berkeley, indicated that there were about 80,000 tons of chloride ion inland from the recharge line within the West Coast Basin prior to injection, assuming an aquifer thickness of 100 feet and a porosity of 30 per cent.[84] This chloride content would degrade the quality of 240,000 acre-feet of ground water to a concentration of 250 parts per million, the generally accepted recommended maximum concentration for domestic use.

Due to the unpredictable effects of the inland advance of the saline wave, waivers were obtained from four ground water pumpers located inland from the test site prior to recharge operations. These waivers stipulated that State agencies connected with the project, and the Los Angeles County Flood Control District, would not be held responsible or liable for damage resulting from test operations.

Derivation of Equation for Fresh Water Waste to Ocean. The Los Angeles County Flood Control District derived an equation for fresh water waste to the ocean from a pressure ridge created to prevent sea-water intrusion. The derivation is based on a combination of the Dupuit-Forchheimer theory and Kozeny's basic parabola solution and appears in Appendix B to this report. The equation is as follows:

$$q = \frac{nKM^2(S-1)}{2L}$$

Where:

q = seaward fresh water flow per foot of ocean front

S = specific gravity of sea water

M = thickness of aquifer, down to the lowest depth which must be protected

K = aquifer permeability for a 100 per cent hydraulic gradient

L = length of sea water wedge, from ocean outlet to the toe

n = coefficient which is less than 1 and depends upon the ratio $\frac{M}{L}$

Test Results. Results of the pressure ridge field experiment indicated that for coastal ground water basins in the State with geologic, hydrologic, and topographic conditions similar to those found at the test site in the West Coast Basin:

1. It is physically possible to raise the piezometric level for a confined aquifer above sea level by injection of suitable water through wells, and thus prevent further intrusion of sea water;
2. It is engineeringly feasible to maintain a pressure ridge above sea level to the extent necessary to prevent sea-water intrusion for long periods of time if the quality of injection water meets certain standards and properly designed injection wells are installed and subsequently rehabilitated by bailing and surging as necessary when injection rates decline. Although injection water may have undergone standard treatment, it must contain sufficient free chlorine at the time of injection to control bacterial activity within the well and adjacent portions of the aquifer. A gravel-packed recharge well, properly sealed with cement grout above the confining clay member to prevent formation subsidence, was found to be the most feasible type of well construction;
3. The rate of recharge required to maintain piezometric levels sufficiently high to halt sea-water inflow along a coastal reach equals the sum of the pre-recharge inflow from the ocean, the amount of recharge water which necessarily wastes to the ocean, lateral flow at each end of the reach, and any small amount entering storage. If a pressure ridge extends along the coast entirely across a completely confined aquifer, the required recharge rate will essentially equal the sum of the first two items, because of the small magnitude of the other two factors. If a pumping trough exists in such a completely confined aquifer, the pre-recharge inland flow equals ground water production seaward of the trough;
4. An aquifer containing water already degraded by sea-water intrusion can be reclaimed for future use. If sea water has advanced inland from the recharge line, certain hazards attend reclamation of the aquifer. Recharging operations will temporarily accelerate the landward sea-water movement immediately inland of the recharge line. If inland ground water producers are located within this area, they might pump water of high mineral concentration sooner than would occur under natural conditions. Although the concentration is probably less than that which would have eventually occurred naturally, the parties responsible for recharge operations might be subject to legal action. In areas where ground water is produced by persons or agencies other than the organization conducting the injection operations, it is recommended that written waivers of possible damage be obtained prior to injection.

Costs. Much less self-evident than the engineering feasibility of creating a pressure ridge by injection through wells to prevent sea-water intrusion is the economic feasibility of such a method. In 1955, the Los Angeles County Flood Control District estimated annual costs of capital recovery and of operation and maintenance of any future project in the West Coast Basin to be $14,900 and $32,000, respectively, per mile. Costs of right of way, pipe line connecting the project with a source of recharge water, and recharge water were not included in these cost estimates. Until such time as more definite plans are evolved as to route of recharge line and source of recharge water, the aforementioned three items of cost will remain uncertain, as will the economic feasibility of such a project.

With regard to the possible sources of recharge water for any future pressure ridge project in the West Coast Basin, the Los Angeles County Flood Control District is presently investigating the feasibility of treating sewage effluent from the City of Los Angeles' Hyperion sewage treatment plant by percolation through slow sand filter beds constructed in the natural sand dune material in the area. This experiment is discussed hereinafter. The Los Angeles County Flood Control District is also studying two other alternative sources: (1) untreated Colorado River water; and (2) treated sewage effluent from a water treatment plant that could be installed adjacent to the Hyperion plant.

Applicability to Other Areas. It was the intent of the Legislature that the results obtained from the pressure ridge field experiment in the West Coast Basin be analyzed and interpreted so as to be usable in the design of similar works for other coastal areas in the State. To carry out this intent, data obtained from the field experiment pertaining to aquifer transmissibility, recharge rate, and height of pressure ridge above the initial piezometric surface, have been analyzed. Inter-relationships between these factors are presented on Plate 30.

If aquifer transmissibility, elevation and slope of the initial piezometric surface, and elevation of the bottom of the confined aquifer in a coastal basin are known, then by use of the curves on Plate 30, the general order of magnitude of the recharge rate necessary to prevent sea-water intrusion can be estimated. The recharge rate obtained through use of these curves is applicable to an initial landward hydraulic gradient and length of sea-water wedge equal to those which existed at the West Coast Basin field experiment. This rate must be multiplied by the ratio of the gradient in the basin under study to the gradient at the experiment, which averaged about 0.004, to ascertain the approximate rate required. Correcting for differences in length of sea-water wedge is not necessary in most cases, since this affects only the amount of injected fresh water wasting to the ocean, which is usually small compared to the rate of injected fresh water movement inland.

If individual well injection rates can be ascertained, possibly from well discharge rate data, approximate number of injection wells required to prevent intrusion can be determined. With these data, it would be possible to complete a preliminary estimate of annual costs of water, capital recovery, and operation and maintenance for a proposed project. Well spacing and well construction costs are primarily dependent upon aquifer transmissibility and type of construction, respectively.

Annual recharge water requirement could, of course, also be obtained if aquifer thickness and permeability and underflow from the ocean, or the ground water production between the proposed recharge line and the pumping trough, were known.

Laboratory Experiments Performed by the University of California at Berkeley

In response to a recommendation in the August, 1951 report of the Division of Water Resources to the State Water Resources Board on proposed sea-water intrusion studies, portions of the investigational program were assigned to the University of California at Berkeley. This agency undertook certain laboratory studies and completed an abstract of technical literature pertaining to sea-water intrusion under terms of State Standard Agreement No. 3SA-423, dated January 1, 1952, and amended December 10, 1952. Funds in the amount of $25,000 were allocated to the University from the appropriation provided under Chapter 1500, Statutes of 1951.

Principal objectives of the laboratory research program were:

1. Determination of shapes and rates of travel of the interface between intruding saline water and displaced fresh water;
2. Study of hydraulic phenomena in connection with the operation of injection wells, including shape and height of pressure mounds or ridges produced thereby;
3. Determination of effect of partial penetration of injection wells into aquifers;
4. Study of types of injection wells and methods of construction thereof;
5. Investigation of phenomena related to the raising of the piezometric surface by rearrangement of pumping pattern;
6. Study of materials and methods related to reduction of aquifer permeability.

In preparing the abstract of literature, all readily available references containing information concerned directly with sea-water intrusion were summarized. Abstracts were divided into the following five categories: (1) reduction of aquifer permeability; (2) sea-water intrusion; (3) injection and recharge of aquifers; (4) laboratory and model studies; and (5) ground water flow.

The University's laboratory research was performed concurrently with the pressure ridge field experiment in the West Coast Basin, previously described. Laboratory and field experiments supplemented each other, including the exchange of basic data and test results, with the work coordinated by representatives of the State Division of Water Resources. In addition, laboratory studies of reduction in aquifer permeability supplemented investigations by the State Water Resources Board and its staff on this subject.

The University's final report on sea-water intrusion laboratory studies and the abstract of literature appear as Appendix C to this report.

Reduction of Aquifer Permeability. The University's laboratory studies were initiated by studying the use of various admixtures to obtain reduction in aquifer permeability. The main item of laboratory equipment developed for these experiments consisted of a permeameter with center and annular screens. Back pressures were regulated to eliminate sidewall leakage around the central core being tested. A constant head reservoir supplied water to the permeameter under a hydraulic gradient of 1,000 per cent. Water was circulated through the samples for periods of up to two weeks; and flow rates were measured by noting the rate of travel of the meniscus in a calibrated narrow-core glass tube.

The first phase of the permeability reduction experiments consisted of adding a thin bentonite slurry having an absolute viscosity of 15 centipoises, similar to the slurry used in oil well drilling, to three different types of material consisting of various proportions of clay, silt, fine sand, and medium sand.

The second portion of the permeability studies was devoted to increasing the viscosity of various slurries by the addition of bentonite in an attempt to further reduce the permeability of the aforementioned three samples. Although a backfill mixture containing only sufficient slurry to fill its voids exhibited a low permeability, it was unworkable. For practicable considerations, emphasis was placed on securing a backfill material which was both workable and suitably impermeable.

The use of cement in decreasing aquifer permeability was investigated by adding 5 and 7½ per cent of cement to a sample containing about 10 per cent silt. Sufficient 15 centipoise bentonite slurry was added to provide a workable mix having a 3 to 4 inch slump.

Asphalt emulsion, 20 per cent by weight, was another material added to 15 centipoise slurry and mixed with a sample containing about 10 per cent silt.

The University's report on their laboratory studies, appearing as Appendix C to this report, presents the following data on unit costs of admixtures, excluding labor costs and costs of gravel, sand, and silt:

1. Assuming a $10 per ton cost for hauling clay, a puddled clay admixture would cost approximately $12 per cubic yard of backfill.
2. Chrome-lignin is estimated by the patent holder to cost from approximately $4 to $11 per cubic yard of backfill.
3. The University estimates that an admixture of one-third clay by weight to equal parts of sand and gravel would cost approximately $4 per cubic yard of backfill, as would a thin bentonite slurry containing 20 per cent asphalt emulsion.
4. For about $0.75 per cubic yard of backfill, seven per cent Wyoming bentonite slurry mixed with an aggregate containing from 10 to 15 per cent silt and 30 to 50 per cent sand, could be provided. The permeability of this mixture would be on the order of 0.001 gallons per day per square foot under a 100 per cent hydraulic gradient, the lowest attained by any of the admixtures discussed. However, this permeability is increased ten-fold in the presence of sea water.

From the results of the University's laboratory tests it was concluded that:

1. Bentonite slurry of a consistency ordinarily used in drilling operations does not produce satisfactory reductions in permeability when added to backfill mixtures containing up to 30 per cent silt.
2. Stiffer slurries, containing from 7 to 8 per cent dry bentonite, promote a satisfactorily low permeability coefficient in well-graded backfill mixtures containing from 15 to 30 per cent silt.
3. It is unlikely that excavation equipment can operate in these thick slurries; even tetra-sodium pyrophosphate was unable to reduce their viscosity appreciably. Unless some material is found that will act in conjunction with the thinner trench slurry to form a satisfactory additive, a separate source of slurry must be used with the backfill mixture.
4. Only enough slurry should be added to the backfill mixture to obtain minimum workability; any additional amount raises its permeability and contributes to the danger of piping. For this reason a method of backfilling should be selected which will allow a minimum amount of water or trench slurry to be incorporated in the mix during placement. Extreme care should also be exercised during backfilling operations to avoid "bridging" of backfill across the cutoff trench.
5. Preliminary data indicate that the permeability to sea water of a mixture incorporating bentonite slurry is roughly ten times its permeability to fresh water.
6. No mixture was found which provided a complete seal. The residual leakage and possible degradation of fresh water inland of the barrier may be determined from the permeability value for the barrier and from a knowledge of ground water level elevations on each side of the barrier.

Model Aquifer Studies. In order to confirm certain theories relating to sea-water intrusion phenomena, a model typifying a pressure aquifer pierced by injection wells was constructed and operated intermittently for about two and one-half years. Paramount objectives were determination of shapes and rates of travel of the interface between intruding saline water and displaced fresh water, amounts of fresh water wasting to the ocean from a pressure ridge, and effect of partial penetration of injection wells into aquifers on creation of a pressure ridge.

The model measured 6 inches high, 3 inches wide, and 4 feet long and was constructed of Lucite. It was packed with a washed quartz sand, Del Monte No. 1, 30 mesh, with an effective grain size of 0.22 millimeters, a uniformity coefficient of 1.3, and a permeability of 0.032 centimeters per second. Chambers were attached at each end of the model and served as constant head sea water and fresh water reservoirs. Piezometer tubes were used to permit measurement of the piezometric surface. Two model injection wells, one-fourth inch in diameter, represented prototype wells approximately 40 feet in diameter. The University believed that this obvious scale distortion would not hinder the model experiments since the flow within a 20-foot radius of prototype wells would for all practical purposes be radial.

The horizontal and vertical scale factors were taken as 1:2,000 and 1:200, respectively, thus representing a section of confined aquifer 100 feet thick and 8,000 feet long. One of the 6-inch by 4-foot vertical rectangular sections of the model represented a section at the internodal point between injection wells, assuming a well spacing of 1,000 feet. The other vertical section represented a section through an injection well. Using the ratios for horizontal and vertical scale, specific gravity, and permeability, and the equation for fresh water flow to the ocean, a time-scale relationship of one minute to 26.7 days was obtained.

Both calcium chloride and sodium chloride solutions with specific gravity of 1.10, were used to simulate sea water in the model. Normal sea water has a specific gravity of 1.025. To distinguish salt water from fresh water within the model aquifer, Rhadamine B was added to the saline water and Fluorosal was added to the fresh water. Use of these fluorescent dyes resulted in a distinctive red sea water and blue fresh water in the presence of ultraviolet light.

The University recorded on motion picture film the salient features of the phenomena illustrated by the model. A 16 millimeter Kodak Cine Special camera with a lapse-time attachment was employed. Prints of this film accompany the University's final report to the State Water Resources Board.

The equation for fresh water leakage to the ocean, which the University derived mathematically using Muskat's approximate potential theory, was checked experimentally by use of the model. The theoretical equation was substantially verified, as shown on Figure 7 of Appendix C. The equation is as follows:

$$Q = \tfrac{1}{2}(S-1)\frac{MT}{L}$$

where:

Q = seaward fresh water flow per foot of ocean front.

S = specific gravity of sea water.

M = thickness of aquifer, down to the lowest depth which must be protected.

T = aquifer transmissibility for 100 per cent hydraulic gradient.

L = length of sea-water wedge, from ocean outlet to the toe.

Since "K" in the previously discussed Los Angeles Flood Control District's equation equals $\frac{``T"}{M}$ in the University's formula, the two equations are identical except that the District's equation contains an additional factor of "$n$." This coefficient "$n$" depends upon the ratio $\frac{``M"}{L}$, and since for most conditions "n" is practically equal to "1," the equation may usually be considered identical. However, since the derivations of the two equations varied widely, the State Division of Water Resources retained Dr. Norman H. Brooks, Assistant Professor of Civil Engineering at the California Institute of Technology, as a consultant to review and report on the derivations. Dr. Brooks' report, appearing in Appendix C to this report, presents three independent derivations based on: (1) Kozeny basic parabola solution; (2) Muskat's approximate potential theory; and (3) Dupuit-Forchheimer theory, all of which corroborated the University of California equation.

The "pumping trough" method of preventing intrusion of sea water was also investigated by use of the model. Water was pumped from the model wells and the rate of movement and shape of the interface were observed, as were the amounts of ocean and fresh water pumped.

Results of the University's experimental model studies indicated the following:

1. In accordance with the Ghyben-Herzberg principle, the fresh water piezometric surface must be maintained above sea level a distance equal to (S—1) times the distance below sea level of the lowest point within the aquifer which must be protected from sea-water intrusion, where S is the specific gravity of sea water;
2. When a pressure ridge is maintained above sea level, the fresh water flow seaward is inversely proportional to length of the sea-water wedge from the ocean outlet determined by the formula previously presented. Fresh water waste to the ocean is independent of the elevation of the aquifer;
3. The total injection rate along the recharge line must be equal to the sum of the fresh water waste to the ocean necessary to maintain the position of the sea-water wedge and the overdraft of the basin originally being satisfied by landward flow of sea water. This relationship may be expressed as follows:

   $$Q = \tfrac{1}{2}(S-1)\frac{M}{L}T + iT$$

   where:

   Q = total injection rate

   i = landward hydraulic gradient prior to injection

   S = specific gravity of sea water

   M = thickness of aquifer, down to the lowest depth which must be protected

   L = length of sea-water wedge, from ocean outlet to the toe

   T = aquifer transmissibility for 100 percent hydraulic gradient

   This relationship is independent of well spacing, location of perforations vertically in the aquifer, individual well injection rates, and well size or type;
4. When conditions are such that the saline wedge moves inland, the wedge tends to flatten out and the toe moves somewhat faster than the remaining interface. In a prototype aquifer, it is believed that nonuniformity of material, with accompanying varying transmissibility, may greatly distort the shape of the interface since the intruding saline water will tend to follow the path of least resistance;
5. Diffusion along the interface is apparently slight as a sharp line of distinction was observed between the sea water and fresh water. It can be expected that some mixing will take place in the immediate vicinity of pumping wells;
6. In areas where the saline wedge has intruded past the recharge line, the wedge will be divided as a result of injection and saline water will be displaced seaward and landward. Injected fresh

water tends to override the severed toe, which becomes flatter as it continues to move inland;

7. Injection well spacing is of little importance, except that the toe of the intruded wedge should be held at least half a well spacing seaward from the injection line. Under this condition, seaward flowing fresh water from the injection wells will have merged to nearly uniform flow as it reaches the toe;
8. Saline-water intrusion can be controlled by establishment of a pumping trough, created by a line of pumping wells parallel to the coast line. Model studies indicate that a saline wedge is created immediately inland from the line of pumping wells similar to the wedge that forms at the ocean outlet, although the wedge inland from the wells is longer for the same fresh water flow seaward. This method of controlling sea-water intrusion would provide no replenishment to a coastal basin, but the loss of fresh water need be no greater than that which would occur with a pressure ridge established through the use of injection wells.

Relative to economic justification for the use of a pressure ridge to control sea-water intrusion, the University recommends that prior to initiation of a field project, the sum of the costs of treating water to be injected, injection, and pumping at a later date be compared with the cost of treating water to an extent necessary to permit its direct use for industrial purposes and some forms of agriculture, plus the cost of surface distribution.

Laboratory Studies Performed by the University of California at Los Angeles

A portion of the investigational program was conducted by the University of California at Los Angeles under State Standard Agreement No. 3SA-430, dated February 1, 1952, and State Standard Agreement No. 53-SA-55, dated January 31, 1953, as amended and reamended on December 17, 1953. The State Water Resources Board allocated $10,000 from funds provided by Chapter 1500, Statutes of 1951, to the University for performance of the experiments.

Objectives of the laboratory studies comprised the following:

1. Determination of the compatibility of treated Colorado River water used as recharge water at the pressure-ridge field experiment in the West Coast Basin, and the native ground water in the vicinity;
2. Treatment of recharge water necessary to maintain suitable permeabilities of core samples secured from the same field project.

Laboratory investigations and the field experiment conducted by the Los Angeles County Flood Control District were coordinated by the State Division of Water Resources. The University's final report of their experiments appears as Appendix D to this report.

Project Facilities. In addition to standard laboratory equipment, Lucite permeameters having an inside diameter of 2½ inches, were provided. These permeameters were fabricated to accommodate 6-inch long cores obtained from the Silverado water-bearing zone during test well drilling at the pressure ridge experimental site. Screens at each end of the permeameters and "O" rings prevented movement of sample particles and "piping" along the periphery of the sample. The core sampler contained a series of 2½-inch outside diameter brass rings, 1 inch wide, to facilitate cutting the sample to any desired length.

Test Procedures. Rings and cores were removed from the core barrel and placed in tin cans, labeled, and sealed in paraffin immediately after coring in the field. Selected cores were then forwarded to the University where cores and rings were inserted into permeameters. Colorado River water from the Metropolitan Water District of Southern California, similar in quality to the recharge water used at the pressure ridge field experiment, was then circulated, untreated and after various types of treatment, through the undisturbed samples. Treatment consisted of the following: (1) chlorination; (2) addition of hydrochloric acid; (3) chlorination plus addition of acid; and (4) deaeration and filtration. Except for a few cores which contained impermeable clay lenses, circulation periods varied from 500 to 5,000 hours. Changes in permeability were noted.

Test Results. The effect of percolating water treated by chlorination plus acidification was to increase permeabilities of cores, even those previously tested with waters which had been treated with acid or chlorine alone. When water treated with acid plus chlorine was percolated through cores previously tested with untreated water, the average permeability increased to 1.4 times the average initial permeability, with one core showing a gain of 30 times its initial permeability. Long-term operation with chlorine-acid treated water might conceivably cause corrosion problems. Therefore, it might be desirable to employ short-term shock treatment using high concentrations of acid and chlorine to maintain satisfactory aquifer permeability without corrosion.

All tests using untreated water and using water treatments other than chlorine plus acid showed significant reductions in permeability. Expressed as percentages of initial permeability, permeabilities after extended percolation (1,000 to 1,200 hours) were 1 per cent using filtered deaerated water, 4 per cent using untreated water, and 15 to 20 per cent using waters treated with chlorine or acid alone. It was also found, with untreated water, that reversing direction of flow had the effect of temporarily restoring a portion of the lost permeability on two samples.

For locations where it is desirable to increase flows of water into injection wells, the report recommends that the effect of treating the water with chlorine and acid be investigated. The report also suggests further experimental work toward creation of a dynamic barrier using air-entrained water as a means of decreasing the quantity of injection water required.

Additional laboratory experiments indicated that the treated Colorado River water used for injection in the West Coast Basin was compatible with ground water in the area. Furthermore, bacteria found in the Silverado water-bearing formation at depths of 150 feet appeared to be aerobic or facultative and in the dormant state. The native environment in the aquifer was found to be anaerobic, however.

Sea-water Intrusion Studies by the United States Geological Survey

The State Water Resources Board allocated $10,000 to the United States Geological Survey, Quality of Water Branch, from funds provided by Chapter 1500, Statutes of 1951, to prosecute water quality laboratory studies pertaining to the chemical aspects of sea-water intrusion. This work was conducted under terms of State Standard Agreement No. 53-CA-3, dated July 1, 1952. The final report describing this investigation appears as Appendix E to this report.

Since ground water underlying portions of the West Coast Basin was thought to be degraded by sea-water intrusion and polluted through improper disposal of oil field brines, and since an intensive ground water sampling program was being conducted in the Manhattan Beach-Hermosa Beach portion of the basin as part of the pressure ridge field experiment, the West Coast Basin was selected for investigation. The laboratory studies were also facilitated by the preponderance of historic water quality data available for the area.

Test Procedures and Results. Approximately 170 ground water samples were collected from various depths, at test wells drilled as part of the pressure ridge experiment. Representatives of the State Division of Water Resources and the Los Angeles County Flood Control District collected the samples by use of portable pumping equipment. Ground water was pumped at each depth until no further change in conductivity of the discharge water was observed, in order to secure a representative sample at the desired aquifer elevation. These samples were analyzed by the United States Geological Survey in Sacramento. Other nearby wells, including several located in the Rosecrans and Torrance oil fields, were also sampled. All sampling was completed prior to initiation of injection at the pressure ridge experiment.

Trilinear plots of selected mineral analyses of ground water from the Manhattan Beach area indicated that ground water in the region was not a simple mixture of ocean water and native ground water. Analyses indicated that ground water in the test area contained more calcium and less sodium than calculated mixtures of native ground water with either ocean water or oil field brines. It was, therefore, assumed that native ground water was either degraded by a highly concentrated calcium and magnesium chloride water, or that the intruding sea water was being altered during intrusion. Connate waters from the Rosecrans and Torrance oil fields did not contain high concentrations of calcium and magnesium chloride. Therefore, the possibility of alteration of sea water was investigated.

Core samples from the Silverado water-bearing zone collected during the drilling of the aforementioned test wells, located approximately one mile inland from the coast, were examined for the presence of exchangeable materials. These wells were located inland from the area of high chloride ion concentration, and it was felt that exchange materials within the aquifer at this location would be largely unaltered. Sea water was circulated through these cores and then analyzed. The concentration of magnesium ions was greater in the effluent than in the sea water, indicating that the cores contained exchangeable materials.

The gain in calcium and magnesium equivalents was not as great as the loss of sodium and potassium equivalents. This can be partially explained by precipitation from solution of a portion of the calcium, either as calcium sulfate or carbonate, subsequent to the base exchange process.

It was also determined that in the highly degraded areas near the coast line little base exchange was occurring at the time, since the exchange capacity of the deposits had been largely depleted. This decrease in base exchange activity was also noted at greater depths where waters of higher sodium concentrations had previously traversed.

Sulfate concentrations in the affected ground water were similar to sulfate concentrations in sea water, indicating further that intruding sea water was the source of degradation. Oil field brines contain much less sulfate than does ocean water.

Since degradation of ground water quality did not increase with decreased distance to the Torrance and Rosecrans oil fields, but did increase with decreased distance to the ocean, it was further concluded that encroachment of ocean water had occurred. Also, degradation increased with depth of aquifer, which would be expected in the presence of an intruding saline wedge.

OTHER EXPERIMENTAL STUDIES

Recharge Tunnel Experiments in Honolulu Area

In 1951, Wentworth proposed that the Board of Water Supply, City and County of Honolulu, Hawaii, undertake certain construction and research projects, including recharge tunnels in Palolo, Manoa, Nuuanu, and Kalihi Valleys.[85] Due to the paucity of data regarding construction and operation of recharge tunnels in formations comparable to those found in the Hawaiian Islands, it was proposed that the initial step be construction of an experimental recharge tunnel to provide data upon which to base future construction plans. Determination of the proportion of recharge water that could be recovered by supply wells was to be a main objective of the experiments.

Construction of a pilot recharge tunnel in Nuuanu Valley was commenced in 1955. The tunnel is presently in operation.[86] The facilities consist of diversion works on a stream below an existing regulatory reservoir, a diversion ditch to the recharge tunnel, and the tunnel itself through which recharge water percolates into the porous lava formation to the water table, where it becomes available for future use.

United States Geological Survey Studies in Florida

The United States Geological Survey is currently engaged in a study of the characteristics of sea-water intrusion along the Florida coast, particularly in the Miami area where the City's well field has been threatened by encroachment. Large swampy areas inland from Miami are being drained as part of land development programs and flood control projects. It is expected that construction of these drainage canals will further aggravate the intrusion problem, both by lowering levels of the underlying fresh ground water to about sea level, and permitting sea water to enter the canals and diffuse downward and laterally into fresh-water aquifers. The limestone aquifer in this area has a thickness of about 100 feet and permeability of about 70,000 gallons per day per square foot.

The Geological Survey reports that a fresh water head of 2.5 feet above sea level is theoretically necessary to prevent intrusion under conditions that exist in the Miami area. Investigators are perplexed as to why intrusion has ceased in recent years with fresh-water levels less than 2.5 feet. Special attention is being given this phenomenon of underground hydrodynamics.

Activities of the High Plains Underground Water Conservation District No. 1, Texas

Decline of ground water levels in portions of Texas as a result of increased use of ground water for irrigation led, in 1950, to enactment of state legislation authorizing the creation of districts "for the conservation, preservation, protection, and recharging and prevention of waste of the underground water of an underground reservoir or subdivision thereof."[87, 88] In 1951, the High Plains Underground Water Conservation District No. 1, with headquarters in Lubbock, Texas, was created as provided by this legislation. The District, comprising 13 counties in west Texas, is not only empowered to require permits for drilling and equipping wells, but also to regulate the spacing of wells and the production therefrom so as to minimize, as far as practicable, the drawdown of the ground water level. In addition, copies of drillers logs and amounts of ground water extractions must be reported to the District. The enabling legislation also permits the District to carry out construction operations and install equipment necessary for recharging ground water supplies, and to carry out research projects in connection therewith.

West Texas is spotted with thousands of land depressions which collect water from direct precipitation, storm runoff, and return irrigation flow. Due to the relatively impermeable soil, this ponded water is disposed of principally by evaporation. Through use of injection wells and shallow recharge pits, ranchers within the District are now recharging the underlying aquifers with part of the ponded water. Most of these injection wells are also used as supply wells, and are pumped for 15 to 30 minutes once or twice a day during recharging operations to remove silt and debris.

University of Arkansas Field Experiments in the Grand Prairie Region

The University of Arkansas, Department of Agricultural Engineering, initiated an experimental recharge well project in the Grand Prairie region of Arkansas in 1954, to determine feasibility, economics, and operational procedures necessary to effect successful recharge of ground waters in the area.[89] Aquifers in the areas under investigation are overlain with impervious clay layers, from 20 to 50 feet thick, necessitating the use of injection wells.

The University reports that their preliminary plans of investigation include determination of the feasibility of using untreated storm runoff for recharge. Although such water will contain silt, it is thought that satisfactory infiltration rates can be maintained by redeveloping the injection wells by periodic pumping.

Pit Injection at Peoria, Illinois

From October, 1952, to May, 1953, a total of 215 million gallons of water were injected through a 40-foot by 62-foot infiltration pit at Peoria, Illinois. The project, which is still in operation, is being conducted by the Illinois State Water Survey with state funds and contributions from Peoria industries.[90] Water is being diverted from the Illinois River to the test pit when the water temperature is below 60° F. and turbidity is less than 100 parts per million. A layer of filter sand in the pit removes much of the silt and clay suspended in the recharge water, resulting in an average injection rate of 1.03 million gallons per day and a maximum rate of 2.0 million gallons per day. In 1955, it was found that injection rates could probably be doubled by using a layer of pea gravel rather than filter sand in the test pit.[91]

Injection Through Wells at King Ranch, Texas

Injection well experiments are being performed near Kingsville, Texas by the King Ranch, with technical assistance by the Humble Oil and Refining Company, to determine if surface pond water can be injected through wells into the overdeveloped underlying aquifer, which has a permeability of about 270 gallons per day per square foot under a 100 per cent gradient.[89] An initial recharge rate of about 800 gallons per minute was attained in an experimental well, but this was drastically reduced when diatomaceous earth filters failed. Subsequent standard rehabilitation operations were not entirely successful and jetting with natural gas at a pressure of 400 pounds per square inch is contemplated. Experiments thus far indicate:

1. Filtration and other treatment of surface pond water is necessary;
2. It is economically feasible to treat recharge water by use of gravel and diatomaceous earth filters;
3. Well injection rates should be kept lower than production capacities;
4. Open-type well screens are more suitable than shutter-type screens, especially when wells are to be redeveloped by jetting.

Studies by the United States Department of Agriculture, Agricultural Research Service, in San Joaquin Valley

The Agricultural Research Service, United States Department of Agriculture, has been conducting extensive field tests in Kern County in San Joaquin Valley, since 1944, to determine recharge techniques in regions of fine grained soils.[91] Vegetative, chemical, and mechanical treatments to increase infiltration rates are being investigated, along with shaft, trench, and pit injection methods. Operational procedures, such as length of wetting and drying periods, and surface head, are also being studied, as are effect of quality of recharge water on recharge rates. The highest infiltration rates have been attained with the addition of cotton gin trash to the spreading basins. Gypsum and krilium also appear to increase infiltration rates when used as an additive to the soil.

Los Angeles County Flood Control District Recharge Tests Near El Segundo Using Reclaimed Sewage

The economic feasibility of maintaining a pressure ridge barrier to sea-water intrusion in the West Coast Basin is, in part, contingent on the availability of an inexpensive source of suitable recharge water. In this regard, the Los Angeles County Flood Control District is currently investigating the feasibility of utilizing treated sewage effluent from the City of Los Angeles' Hyperion treatment plant, and storm runoff from the Westchester area and from the Los Angeles International Airport, to maintain the pressure ridge.[92]

In the District's experimental installation, sewage effluent is pumped from the secondary treatment facilities of the City's plant to a 0.7-acre oxidation and settling basin from which it flows to two 0.5-acre percolation basins. These basins are located in the coastal sand dunes immediately south of the treatment plant; and the quality of the ground water underlying the area is essentially the same as sea water. There are approximately 13 feet of wind-blown permeable dune sand underlying each basin. This material has an exceptionally uniform grain size and overlies cemented sands, which are relatively impervious. Samples of percolated effluent are obtained at 3-foot, 5-foot, 7-foot, and 10-foot depths at each basin by use of a vertical shaft and sampling pans.

Infiltration rates have varied considerably, ranging from about 20 feet per day to several inches per day and averaging approximately one foot per day. Declining rates have necessitated drying and scarifying the west percolation basin every three to five weeks. A 2-foot depth of water was originally maintained at all times in the east percolation basin. To maintain suitable infiltration rates, this basin was "wet plowed" every four to six weeks. This entailed pulling a plow across the basin, through the water, by a system of ropes and pulleys. However, it was found necessary to intermittently dry and scarify this basin also to re-establish satisfactory rates. Results of basin spreading are set forth in the following tabulation:

Item	*Continuous spreading* *Without raking*	*With raking*	*Intermittent spreading*
Percolation rate (cfs/wetted acre)	0.15	1.0	0.5
BOD (ppm)			
Basin influent	35	42	31
Basin effluent	7	7	2
Reduction (per cent)	80	83	93
Suspended solids (ppm)			
Basin influent	38	71	55
Basin effluent	4	15	11
Reduction (per cent)	89	79	80

These results generally corroborate findings of prior field tests by the Los Angeles County Flood Control District at Whittier in 1948, and Azusa in 1949, involving recharge of sewage effluent.

Following analysis and evaluation of the preliminary test data, the District proceeded to investigate the injection of the effluent obtained from drains beneath the basins. A gravel-packed recharge well was installed for that purpose near the test site. Three 8-inch wells were drilled for observing changes in ground water quality and gradients in the vicinity. Chlorinated fresh water was injected through the well initially, but since July, 1956, sewage effluent from the drains has been injected at a rate of about 0.3 second-foot. During one 127-day test period, with an injection head not exceeding 46 feet, the biochemical oxygen demand of the injected water averaged 1.5 parts per million and the suspended solids content averaged 13 parts per million. Chlorination to a residual of 0.1 part per million has been effective in limiting the coliform bacteria count in the recharge water to meet United States Public Health Service drinking water standards. About every five weeks, the recharge well is reactivated by bailing, surging, and adding aggregate to the gravel envelope.

Due to the difficulties and costs associated with acquiring necessary lands along the coast of the West Coast Basin for use as natural filtering basins, the Los Angeles County Flood Control District installed a pilot "polishing" treatment plant adjacent to the Hyperion sewage treatment plant. Objective of the studies was to determine what "polishing" treatment of the effluent from Hyperion would be required to provide water of suitable quality for injecting through wells. These experiments consisted of use of trickling filters with subsequent sedimentation, rapid sand filters, and intermittent high-rate spreading. Field work had been completed and test results were being analyzed at the time of preparation of this report.

CHAPTER VI

ECONOMIC AND LEGAL CONSIDERATIONS

ECONOMIC ASPECTS OF SEA-WATER INTRUSION

The principal economic effect of sea-water intrusion is believed to lie in the impairment of the intruded ground water basin as an underground storage reservoir and as a source of water supply. It is this effect which is treated in the following discussion. Other consequences, such as damages resulting from excessive salinization of soils, are usually of lesser significance. Such losses, where applicable, would be added to those resulting from curtailment of the ground water supply in the economic evaluation of any specific sea-water intrusion problem.

From an economic standpoint, there are three alternatives available to an area faced with a present or potential sea-water intrusion problem. First, it can be decided that no action be taken, in which case economic activity and expansion would probably be supplied largely by mining of accumulated ground water reserves. Exhaustion of that accumulation would eventually require drastic curtailment of activity. The second choice is to limit agricultural or industrial activity to a level that is within the capabilities of the basin safe yield. It should be noted that the safe yield of the basin can vary considerably, depending on whether measures are taken to prevent or control sea-water intrusion. The third alternative is to take positive action to insure continued growth by timely provision of additional supplies. To determine the most desirable action from an economic standpoint, the benefits and costs of each proposed alternative should be assessed, and the program which would maximize the use of land, labor, and capital be ascertained.

Some Consequences of Inaction

In most ground water basins in California confronted with sea-water intrusion problems, development of the economy has been based on exploitation or "mining" of ground water supplies accumulated over untold centuries of time. In such cases, the economic structure is larger than can be supported by the safe yield of the basin. As the accumulated supply becomes depleted and the basin becomes degraded by the advancing sea water, more and more water wells will have to be abandoned. Unless an alternative supply is found, the farms dependent on those wells must revert to dry-farm status. Likewise, if an urban economy finds itself in these straits, and nothing is done to alleviate the situation, the activities dependent upon the wells in question would have to be discontinued. Ultimately, if no corrective action were taken, a once flourishing community could become little more than a ghost town.

If a decision is made that a plan of protection or importation is infeasible, advance planning can insure that disinvestment will be orderly, whereas unplanned inaction would result not only in larger economic losses occurring but also in the social losses of dislocation. Neither situation appears to have occured in California to date. However, in several instances, supplemental water supplies have been imported from great distances at heavy cost. It becomes less possible to avoid the consequences of inaction as the size of the community, rural or urban, decreases, as the isolation of the area increases, and as the distance to water sources increases.

Protection of Safe Yield

The second general course of action involves the protection of the safe yield of the ground water basin. This implies the stabilization of economic activity at a level consistent with the safe yield. As was previously stated, the safe yield of a coastal ground water basin can depend upon whether or not measures are taken to protect the basin from sea-water intrusion. A decision as to whether to undertake such a plan of protection would require an evaluation of its costs and benefits. This evaluation would involve at least two major phases. One consists of assessing the economic consequences of a reduction in the water supply resulting from sea-water intrusion. The second phase involves determination of the cost of construction of protective works and comparison of the two amounts to determine the economic justification. A third phase might be a separate analysis to determine whether sufficient financial resources are available to carry out the project. There might be alternative methods of providing an annual supply equivalent to that provided by the proposed plan of protection, such as a system for importation or for re-use of water. In this case, a direct comparison of costs would reveal the most economical project.

Factors which bear on the evaluation of alternative courses of action include present and potential land-use patterns, water requirements, the safe yield of the basin under various conditions and the costs of production of these yields, the cost of protective works, and cost of imported water. A significant consideration in determining any course of action is the possible use of the ground water basin as a storage reservoir, regardless of the source of water. The relative stages of development of the urban and agricultural portions of an area overlying a ground water basin would determine to a great extent the types and quantity of losses which would occur.

Urban Development. In urban areas, the ideal evaluation of losses would consist of a determination, unique for each community, of its income structure, characteristic activities, and those activities most sensitive to a decrease in water supply. These losses would be difficult to evaluate, consisting as they would in the decrease in net income to business abandoned and in equivalent rental value of dwellings lost through the decrease in water supply. Indirect or secondary losses would also accompany a curtailment of urban activities. These losses are even more difficult to assess.

It is believed that in most cases the losses involved in a curtailment of urban activities would be far greater than the cost of providing an alternative water supply. If a combination of works for the importation and/or re-use of water produced a supply less costly than that of an equivalent plan of basin protection, the protected safe yield of the basin would not be significant from an economic point of view until such time as the community expanded to the extent that the imported supply was completely used.

Agricultural Development. The course of action to be followed in an agricultural area would involve a determination of the reduction in irrigated acreage caused by sea-water intrusion, and the difference in net income and farm investment values between a dry-farm and an irrigation economy on that acreage. The annual loss could be evaluated in the following steps: (1) determination of the difference in acreages capable of irrigation under conditions of basin protection and of no protection; (2) estimation of the probable annual net farm incomes and farm investment values on the differential acreage, assuming the best combinations of crops under irrigation and under dry farming; and (3) determination of the capital equivalent or present worth of the difference in net income estimated from (2), assuming a suitable rate of interest. The present worth of the losses, as computed in step (3), would be compared with the cost of the plan of protection, to determine the economic desirability of the plan. As indicated previously in the section on urban development, it is possible that a scheme of importation could be less costly, in which case this plan would be tested against the losses to determine its feasibility. Regardless of the method of providing the incremental water suply, the margin of profit to irrigators from that supply should be sufficient to warrant taking the risks involved.

Increase in Supply Through Utilization of Imports

The third alternative course of action is the timely provision of imported supplies to sustain the growth of an economy that was developed by "mining" of a ground water basin. Until ground water extractions have proceeded to the point at which the basin would be jeopardized by further withdrawals, there normally would be no reason why the "mining" should not continue. A problem exists, of course, in determining when the critical point is reached. Another problem concerns the rate of "mining" as it affects possible over-capitalization. In the case of agriculture, more acreage might be brought under irrigation than could be sustained by the safe yield of the basin under conditions of basin protection. This high level of irrigation could ultimately be sustained only if the necessary import works could be financed. An urban area developed on the basis of "mining" might be brought to such an economic level that expensive works for the importation of water could be financed, thus not only maintaining but further expanding the economy.

In some cases, preservation of safe yield is a secondary consideration in the provision of works designed to protect a basin from sea-water intrusion. Where the ground water basin is largely a pressure aquifer, there is little or no storage available for conservation of local runoff. The main purpose of such protective works might then be the complete exploitation of the accumulated ground water supply and, where appropriate, the efficient distribution of an imported supply or of reclaimed sewage. The cost of the protection works would have to be balanced primarily against the value of reclaimed sewage as a water supply and against the cost of the works required to achieve surface distribution of the required imports—and only to a minor degree against the actual loss of local safe yield.

Other Considerations

In some areas, continued expansion of an urban economy will require the importation of large quantities of water and provision of facilities for regulation and distribution of these imports. Under such circumstances, the utility of a ground water basin for "peaking" and regulatory storage could represent additional justification for basin protection. The economic evaluation of the protection works for peaking purposes would involve comparison of the costs of two surface systems—one having the larger capacities required in the absence of supplemental peaking facilities, and the other a smaller system made possible by use of the ground water basin.

Another possibility in some basins, which would also have to be evaluated in terms of costs and benefits, is the mixture of partially degraded water from the basin with a fresh imported supply providing water of sufficiently high quality for specified purposes. In this case, the cost of protection works would be balanced against the losses resulting from the net level of degradation anticipated in the absence of such works.

The maintenance of a ground water supply by the construction of basin protection works might not be wholly subject to explicit economic evaluation. An important function of such a supply might be to support a population during time of war if surface systems were disrupted or contaminated by enemy attacks. Surface water supplies are vulnerable to disruption by high explosives and sabotage. They are also subject to the hazards of contamination by radioactive fallout and by bacteriological warfare. As a standby source, the ground water basins, which are relatively immune to such perils, would then be invaluable. Also, a protected ground water basin would be insurance against unforseen periods of drought, when other supplies might be curtailed or unavailable.

Economic Planning Required for Choice of Alternative Courses of Action

It has been stated that a decision whether or not to undertake a particular project depends upon: (1) a comparison of the benefits and costs of the project, and (2) a comparison of the cost of the project with costs of other means for accomplishing the same ends. In terms of the three major alternatives previously set forth, those responsible for making water policy in a coastal ground water basin must essentially carry out this type of analysis. Each possible course of action has its costs and benefits, and if these can be defined with sufficient clarity, the various plans can be compared to determine the one best plan. The extent to which "mining" of accumulated ground water supplies should be carried, the timing of construction for basin protective works, the provision of facilities for re-use of water or reclamation of sewage, and the decision as to size and timing of import works are all subject to the kind of analysis herein indicated. It is possible that some combination of plans can turn out to be the most advantageous. It could also be that the cost of importation works would be prohibitively expensive. In this case, the best course would consist of completely exploiting the local supply and subsequently relocating those activities which could no longer be supported.

In a given area, the larger the economic and social grouping involved in a decision, the more alternatives there are from which to choose. This being the case, there is more opportunity to find the course of action which will be most advantageous. For instance, with reference to import of supplemental supplies, it behooves local interests to cooperate to the fullest extent, to the end that the most economically advantageous supply be obtained.

LEGAL ASPECTS OF SEA-WATER INTRUSION

The feasibility of any proposal for prevention of sea-water intrusion may well hinge upon legal considerations. Effective and economical prevention or elimination of sea-water intrusion must necessarily involve planned use and management of the threatened ground water basins.

An effective method of controlling extractions in these basins is essential to any such program. Also, in many cases, it is necessary to modify the pattern of pumping. Such planned utilization of the coastal ground water basins is necessary, not only to control sea-water intrusion, but also to bring about their maximum utilization to meet the needs of the water users.

In any effective, long-range program for the prevention of sea-water intrusion, it may be necessary to determine the water rights of those using water from the basin. Information as to these rights is of great assistance in making an equitable division of the costs of mutual protection. Where, through planned utilization of a ground water basin, its regimen is materially changed, it will also be necessary to have information as to the rights of the water users in order to furnish them with the quantity of water to which they are entitled, or, in some cases, to properly compensate them for interference with their rights.

The prevention of sea-water intrusion is but one phase of the required program for planned management of ground water basins that is necessary to effectuate The California Water Plan. The legal problems that are involved in such planned utilization of ground water basins are discussed in Department of Water Resources Bulletin No. 3, "The California Water Plan," May, 1957, and those considerations will not be reviewed here. Consideration will be given, however, to the adequacy of present laws to authorize measures necessary for the prevention of sea-water intrusion, including planned management of ground water basins; and to the adequacy of present procedures for the determination of rights to the use of ground water.

Authority to Control Sea-Water Intrusion

Under present law, no administrative agency of the State is empowered to take all necessary actions to prevent and control sea-water intrusion. The Attorney General's office, in a letter to the State Water Pollution Control Board dated November 2, 1950, stated that the enforcement responsibility and authority of the State and Regional Water Pollution Control Boards extends only to impairment of water quality caused by discharge of sewage and industrial waste. Under Section 229 of the Water Code, the Department of Water Resources is directed to investigate and report upon the quality of all waters within the State, including saline waters, coastal and inland, as related to all sources of pollution of whatever nature. This provision has been broadly interpreted to encompass all types of water quality problems, including sea-water intrusion. The Department is directed to report to the Legislature and to the appropriate Regional Water Pollution Control Board; and its reports may recommend any steps which might be taken to improve or protect the quality of waters of the State. However, as related to the jurisdiction of the Water Pollution Control Boards, pollution is narrowly defined in Section 13005 of the Water Code to mean ". . . impairment of the quality of waters of the State by sewage or industrial waste . . . ."

The methods of preventing sea-water intrusion that have been set forth in Chapter IV of this study are:

(1) Reduction of pumping or rearrangement of pumping patterns.
(2) Recharge of the basin (ordinarily with imported water) to bring ground water levels up to or above sea level.
(3) The creation of a coastal fresh-water ridge through spreading or injection.
(4) The construction of an artificial subsurface physical barrier.
(5) The creation of a pumping trough along the coast.

Under present statutes, there is no district or state agency which has authority to require a reduction of pumping or rearrangement of the pumping pattern except under a voluntary agreement among the parties to be affected. In the absence of such agreement, either of these objectives could be accomplished only in a court proceeding. The *Raymond Basin* case (to be discussed subsequently) is a precedent for the authority of the courts to order necessary reductions in pumping from ground water basins. The logical extension of this principle, combined with the well established authority of courts to impose a physical solution in water rights cases, would indicate authority to require a rearrangement of the pumping pattern. As yet, however, this has not actually been done. Since rearrangement of the pumping pattern would probably require the construction of physical works to supply water to the area of diminished pumping, it would probably have to be accomplished by the court with the cooperation of a proper district or state agency. In this connection, it should be noted that the State Water Rights Board can, after filing of its report in a court reference proceeding, seek an injunction under Water Code Section 2020 to have pumping restricted in order to curtail sea-water intrusion in the five southern California coastal counties (Santa Barbara, Ventura, Los Angeles, Orange and San Diego).

A number of districts have the authority to recharge ground water basins. Of special interest are the Water Replenishment Districts which can be established under Division 18 of the Water Code in the Counties of Santa Barbara, Ventura, Los Angeles, San Diego, Riverside and San Bernardino; and that portion of Orange County not included within the Orange County Water District. These districts are specifically designed for ground water replenishment. The Orange County Water District is also authorized to engage in ground water replenishment activities.

Water Replenishment Districts have the advantage of being authorized to levy assessments in proportion to ground water pumpage. This is particularly important in making equitable assessments on those holding appropriative and prescriptive rights to use water on non-overlying land, since these water users might not be adequately assessed on an *ad valorem* basis. Such districts also have the power (Water Code § 60221) to distribute water in exchange for ceasing or reducing ground water extractions for the purpose of replenishing the ground water supplies within the district. Thus, through voluntary arrangements, modifications of pumping patterns could be achieved.

As yet, no Water Replenishment District has been organized, although one is in the process of organization in Los Angeles County. Because of the advantages of this type of district in effectively utilizing ground water basins and controlling saline intrusion, consideration should be given to extending the coverage of the Water Replenishment District Act throughout the State.

In 1953, The Orange County Water District Act [Cal. Gen. Laws 1954, Act 5683 (Deering)] was amended to give the District powers to assess on the basis of water pumped from the underground. The validity of these powers was sustained in *Orange County Water District* v. *Farnsworth*, 138 Cal. App. 2d. 518, 292 P. 2d. 927 (1956). This decision also constitutes a precedent for the validity of this type of assessment by Water Replenishment Districts.

Although there is some question, which it might be well to resolve by appropriate legislation, a Water Replenishment District could probably maintain a fresh-water ridge, construct a subsurface barrier, or maintain a pumping trough to protect a ground water basin from intrusion of sea water. These doubts could be removed by expanding the powers of these districts to include specific authority for control of sea-water intrusion. A number of other districts could also accomplish these deterrents to sea-water intrusion under their general authority to conserve water.

Another essential ingredient of the program for preventing sea-water intrusion is the control of extractions from the affected basins. The situation is particularly acute in coastal basins because sea-water intrusion may irreparably injure the basin as a source of water supply, or may cause damage that can only be corrected over a period of many years and at a great expense. Because of the great economic hardship that drastic limitations of pumping might cause, this remedy could well remain with the courts and not be exercised by governmental agencies. Since the limitation of extractions from a ground water basin must be preceded by an authoritative determination of the rights of the water users, it is logical that the court should have the final authority.

In addition to the authority to carry out the specific proposals for the prevention of sea-water intrusion that have been discussed, statutory authority is needed for the planned management of ground water basins. As pointed out previously, only the courts now have such authority. Legislation to provide such authority to the State or to local agencies would make it possible to require rearrangement of pumping patterns. It would also make it possible to utilize coastal ground water basins to store water during wet periods for use during the ensuing dry years, as contemplated in The California Water Plan. Any such legislation must, of course, provide full protection for vested rights to the use of ground water. Because of the far-reaching changes that planned utilization of ground water basins would cause in relation to the thousands of individual water users, a constitutional amendment to authorize this practice may be desirable. A principal function of such an amendment would be to make sure that the injunctive process would not be used to delay or prevent such programs. Although this policy may already be established in California, any doubt could be allayed by specific provisions that the user of ground water must accept compensation either through the furnishing of water (a physical solution) or by way of monetary damages.

At present, the procedures in the Water Code for appropriation of unappropriated water do not apply to ground water basins. Consideration should be given to legislation that would extend to percolating ground water the procedure for the filing of applications and the granting of permits and licenses to appropriate. Through this means, more accurate records could be obtained as to extractions, and conditions could be imposed in the public interest that would provide for better management of basins.

Determination of Water Rights

Each owner of land overlying a ground water reservoir has a paramount right to the reasonable beneficial use of the water underlying his tract [*Miller* v. *Bay Cities Water Co.*, 157 Cal. 256, 107 P. 115 (1910)]. This right is generally analogous to riparian rights to surface flow [*Burr* v. *Maclay-Rancho Water Co.*, 154 Cal. 428, 98 P. 260 (1908)]. Furthermore, the underground supply must be shared by all, and the right of each owner is correlative to that of every other similar owner [*Katz* v. *Walkinshaw*, 141 Cal. 116, 70 P. 663, 74 P. 766 (1902)]. Overlying rights can be lost by *laches* or prescription.

Appropriative rights to surplus ground water can now be acquired by taking the water. Unless they have developed into prescriptive rights through adverse use, they must yield to the rights of overlying owners. As mentioned previously, there are no statutory provisions for licensing of ground water appropriations, as is provided in the case of surface waters.

Determinations of basic water rights would make possible a more equitable distribution of costs, no matter what type of sea-water intrusion control program is adopted; and would furnish a basis for a physical solution or the payment of damages. Present methods of determining water rights include:

a. Voluntary agreement among water users;
b. Statutory adjudication procedure;
c. Court reference procedure;
d. Civil suits without reference.

It seems improbable that agreement could be reached on a voluntary basis for a basin supplying any considerable number of water users. The statutory adjudication procedure is limited by present law to determination of rights to surface streams and to subterranean streams flowing through known and definite channels. It is seldom that ground water basins fall definitely in the latter category. This procedure is therefore not generally available for the contemplated purpose.

Under the court reference procedure, the court can refer the action to the State Water Rights Board for investigation and report upon any or all of the physical facts involved. The report may include a recommended solution. This procedure is applicable to all types of water rights suits and has been frequently used in suits involving rights to surface streams. It has also been used in the several actions involving ground water, one of which has been carried to the Supreme Court of California and also the Supreme Court of the United States [*Pasadena* v. *Alhambra*, 33 Cal. 2d 908, 207 P. 2d 17 (1949) certiorari denied sub nom, *California-Michigan Land and Water Co.*, v. *Pasadena*, 339 U. S. 937 (1950)]. The decree of the Superior Court in this action was affirmed as modified and the court reference procedure was approved. This case is commonly referred to as the Raymond Basin case. It affords a firm precedent for recourse to the court reference procedure in suits involving the determination of rights to the use of ground water constituting a common source of supply, and for exercise by the court of power to impose adequate control of ground water extractions to prevent continued overdraft. The case also affords a firm precedent for the trial court in its decree to retain broad jurisdiction, to make changes in the decree from time to time as occasion may require, and to appoint the Department of Water Resources or another agency as watermaster to enforce the decree.

In the Raymond Basin case, sea-water intrusion was not involved. However, it is considered that the hazard to the continued availability of ground water by sea-water intrusion, due to continued overdraft, establishes ample basis for invoking the power of the court to impose control over extractions as was done in the Raymond Basin case. In this connection, water rights actions in the West Coast Basin of Los Angeles County, and in Tia Juana Basin of San Diego County, have been referred to the State Water Rights Board for investigation.

It is also possible to adjudicate rights to the use of water from a common ground water source by court procedure without reference. In the determination of rights for an entire ground water basin, such court procedure will generally be more expensive and time-consuming than the reference procedure, with less productive results.

It follows that recourse to the court reference procedure is the most practicable and feasible means available under existing law whereby the State may afford legal and technical assistance in the formulation and imposition of a physical solution adequate to remedy continued overdraft on a common supply of ground water which has resulted in intrusion of ocean water to such an extent as to threaten availability of such common supply for beneficial uses. Under this procedure, all possibilities of a feasible physical solution can be fully explored, assistance of trained specialists in the field of ground water geology and hydrology can be made available to assist the court and the parties in the formulation of a just and equitable solution to ground water problems, and such solution can be fully effectuated. However, in many cases, even the court reference procedure is lengthy and expensive, and could be materially improved in several respects. Consideration should be given to legislation that would improve the court reference and statutory adjudication procedures, and extend the latter to ground water basins.*

* For a discussion of many of the legislative proposals that have been suggested here, see statement of Henry Holsinger, then Principal Attorney, Division of Water Resources (now Chairman, State Water Rights Board) to Joint Legislative Interim Committee on Water Problems, December 14, 1954.

CHAPTER VII

PLANS FOR PREVENTION AND CONTROL OF SEA-WATER INTRUSION

Selecting a method, or methods, for prevention and control of sea-water intrusion involves consideration of many factors, as discussed in Chapter IV. These considerations should be carefully analyzed and evaluated prior to selection of control methods. This may involve an investigation of the following factors:

1. Depth, thickness, extent, and transmissibility of water-bearing formations; and barriers to ground water movement.
2. Occurrence, movement, and quality of ground water.
3. Amount and areal distribution of extractions from the basin.
4. Availability, cost, and quality of recharge water.
5. Availability and cost of right of way for artificial recharge projects.
6. Availability and cost of an alternate water supply, if use of ground water is to be curtailed.
7. Benefits accruing from optimum utilization of underground storage.
8. Salt balance.
9. Organizational and management problems connected with basin or project operation.
10. Water rights.
11. Economic feasibility.
12. Financial feasibility.

In many areas in the State where intrusion has occurred, federal, state, and local agencies have made comprehensive investigations of geologic and hydrologic conditions. In some instances, local agencies have constructed facilities to control, in part, further intrusion.

Conditions within the nine areas where sea-water intrusion is known to have occurred have been studied to determine which method, or methods, of control might be utilized for prevention of further intrusion. Possible plans for each of these areas are discussed in this chapter, and set forth in Table 2.

PLANS FOR AREAS OF KNOWN SEA-WATER INTRUSION

Petaluma Valley

The several methods based on raising ground water levels above sea level appear to be most suitable for preventing sea-water intrusion in Petaluma Valley, Sonoma County. Among these are reduction of extractions, basin-wide recharge of aquifers, or maintenance of a fresh-water ridge along the coast. Construction of an artificial subsurface barrier parallel to the coast is not considered feasible, since the Quaternary alluvium is over 300 feet deep in the bayward portion of the valley. Furthermore, an unknown depth of older alluvium underlies these sediments.

It is felt that rearrangement of the pumping pattern would not be effective in Petaluma Valley since ground water withdrawals in the bayward portion of

TABLE 2

POSSIBLE METHODS FOR PREVENTION AND CONTROL OF SEA-WATER INTRUSION IN AREAS WHERE INTRUSION IS KNOWN TO HAVE OCCURRED

Area	Raising of ground water levels above sea level by reduction or rearrangement of pattern of pumping draft	Direct recharge of overdrawn aquifers to maintain ground water levels at or above sea level[a]	Maintenance of a fresh water ridge above sea level along the coast[a]	Construction of artificial subsurface barriers	Development of a pumping trough adjacent to the coast
Petaluma Valley		X	X		
Napa-Sonoma Valley		X	X		
Santa Clara Valley	X	X	X		
Pajaro Valley	X	X	X		
Salinas Valley Pressure Area	X	X	X		
Oxnard Plain Basin	X	X	X	X	
West Coast Basin	X[b]	X[b]	X		
East Coastal Plain Pressure Area	X	X	X	X	
Mission Basin	X	X	X	X	X

[a] Assumes recharge water available.
[b] This method would be effective only if also applied in the remaining portions of Coastal Plain, Los Angeles County.

the valley are not significant. Most ground water development now occurs in the inland portions of the area.

Unless an industrial demand should develop for brackish water, the use of a pumping trough adjacent to the coast to prevent sea-water intrusion does not appear to be feasible.

There are at present no projects under way to control sea-water intrusion into aquifers underlying Petaluma Valley. At present, imported water is not available to supplement overdrawn ground water supplies, and it is doubtful whether it would be feasible to maintain ground water levels above sea level until such supplies become available.

The North Bay Aqueduct, authorized for construction by Chapter 2252, Statutes of 1957, as a unit of The California Water Plan, would provide a firm supplemental supply to Petaluma Valley. This facility would divert water from the Sacramento-San Joaquin Delta, about 15 miles east of the City of Fairfield, and terminate in Novato Reservoir about ten miles southeast of Petaluma. The aqueduct, which would supply the needs of Petaluma Valley until the year 2010, is described in Department of Water Resources Bulletin No. 60, "Interim Report to the California State Legislature on the Salinity Control Barrier Investigation," March 1957.

When supplemental supplies are secured, it may be possible to raise ground water levels above sea level through spreading operations without the use of wells, due to the absence of confining clay strata. Final selection between raising ground water levels above sea level throughout the entire basin, or maintaining a fresh-water barrier parallel to the coast would require extensive engineering, economic, and financial studies.

Napa-Sonoma Valley

Napa-Sonoma Valley is similar to Petaluma Valley in that the most feasible method of controlling sea-water intrusion appears to be importation of supplemental water to be used, in part, to raise ground water levels above sea level throughout the entire basin or to operate a fresh-water barrier parallel to the coast. The aforementioned North Bay Aqueduct would provide such a supplemental supply. As in Petaluma Valley, it may be possible to maintain water levels above sea level through spreading operations without the use of wells. Selection of the best of these two methods would be based on economic and financial aspects, including the benefits obtained from fully utilizing the storage capacity of the ground water basin. Further hydrologic and geologic studies may be required.

Due to the 300- to 500-foot depths of unconsolidated alluvium along the bayward margin of the Napa-Sonoma Valley, use of an artificial subsurface barrier to prevent further intrusion does not appear engineeringly or economically feasible.

Like Petaluma Valley, there is little ground water development in the bayward portions of the basin and, therefore, change in pumping pattern would not assist in controlling intrusion. Also, unless an industrial demand for brackish water should develop, the use of a pumping trough adjacent to the coast to prevent intrusion does not appear feasible.

None of the methods of control of sea-water intrusion, as outlined previously in this report, have as yet been attempted in this valley.

Santa Clara Valley

Importing supplemental water and raising ground water levels above sea level along the coast appears to offer the only permanent solution to the problem of sea-water intrusion in the Santa Clara Valley. This could be accomplished by maintaining a fresh-water ridge. However, a change in pumping pattern and reduction of pumping draft, coupled with the use of supplemental water, would also halt encroachment of saline water, particularly in the Palo Alto-San Jose area. If ground water withdrawals adjacent to the coast were reduced and withdrawals further inland were comparably increased, the existing landward hydraulic gradient would be flattened, thus decreasing the rate of intrusion.

There are presently 24 artificial recharge projects located in the Santa Clara Valley, 3 of which are operated by the Alameda County Water District and the rest by the Santa Clara Valley Water Conservation District. These conservation programs have undoubtedly reduced the rate of ground water level decline.

Portions of the Santa Clara Valley are receiving an imported supply from the Tuolumne River through the Hetch Hetchy Aqueduct of the City of San Francisco, and from the Mokelumne River system through facilities of the East Bay Municipal Utility District. The valley is in the area to be served by the proposed South Bay Aqueduct, a feature of the authorized Feather River Project. Existing and proposed water development facilities are described in State Water Resources Board Bulletin No. 7, "Santa Clara Valley Investigation," June, 1955.

Depth of alluvium along the 80 miles of the Santa Clara Valley coast line which are open to San Francisco Bay is as great as 1,000 feet. Thus it appears infeasible to construct artificial subsurface barriers to prevent further intrusion of saline water from San Francisco Bay. Unless a commercial need for brackish water should arise, the use of a pumping trough adjacent to the coast to prevent sea-water intrusion does not appear to be feasible.

In areas where surficial clays are nonexistent or readily removed, it might be feasible to prevent further encroachment of sea water into the upper aquifer by creating a fresh-water ridge through a series of recharge basins parallel to the coast. However, the use of injection wells would be necessary to maintain a coastal pressure ridge in the pressure aquifers. Although there would be some waste of fresh water to San Francisco Bay attendant with maintenance of a fresh-water mound or pressure ridge, this method of control would permit better utilization of the vast Santa Clara Valley ground water basin and would increase the safe yield therefrom.

Pajaro Valley

A supplemental source of water to serve as a direct supply to coastal pumpers would be required to permanently control sea-water intrusion in the Pajaro Valley. Supplemental supplies might also be used to maintain a pressure ridge adjacent to the coast. Since both water-bearing zones adjacent to the coast are confined, the use of injection wells to create a ridge would be necessary. However, some reduction in encroachment of sea water could be achieved if ground water withdrawals in the area east and southeast of Watsonville were increased and ground water pumping southwest of Watsonville near the coast were decreased accordingly. Furthermore, this change in pumping pattern would probably induce increased subsurface inflow to the coastal confined aquifers from the forebay area, and ground water safe yield might be increased.

Since only three miles of the valley are open to Monterey Bay, it would seem, at first glance, that use of an artificial subsurface barrier would be the most desirable method of preventing further sea-water intrusion. However, the base of the main pumping zone lies as much as 300 feet below land surface in certain areas; and a deeper water-bearing zone underlies the main zone. In view of limitations of present construction equipment and techniques, it is not considered feasible to construct subsurface barriers to these depths.

Development of a pumping trough adjacent to the coast is not considered feasible in this valley.

Supplemental water supplies could be secured by importation or further development of local supplies, such as would be afforded by the proposed Watsonville Project, described in State Water Resources Board Bulletin No. 5, "Santa Cruz-Monterey Counties Investigation," August, 1953. Preliminary studies undertaken in 1957 indicate that the Feather River Project would be the most feasible source of imported water, which could be diverted from the proposed San Luis Reservoir in the San Joaquin Valley and conveyed by tunnel beneath Pacheco Pass.

Salinas Valley Pressure Area

Planned operation of coastal and inland ground water basins for the benefit of overlying users, in conjunction with use of surface water supplied from upstream storage facilities appears to be the most feasible method of local water development and prevention of sea-water intrusion. The largest upstream storage facility is Nacimiento Dam on Nacimiento River in San Luis Obispo County, which was completed in 1956 for the Monterey County Flood Control and Water Conservation District. The reservoir has a storage capacity of 350,000 acre-feet; and releases percolate in the natural channels of the Nacimiento and Salinas Rivers, replenishing, in part, the ground water basins and thus retarding sea-water intrusion. Bulletin No. 19 of the Department of Water Resources, "Salinas River Basin Investigation," currently under preparation, describes plans for local water supply development and importation of waters from other areas.

Rearrangement of pumping pattern by reducing ground water withdrawals in the area between Salinas and the coast would, of course, flatten the landward hydraulic gradient and decelerate the intrusion rate.

Water-bearing sediments along the coastal periphery of Salinas Valley in which most of the wells are perforated, are up to 300 feet thick. Therefore, use of an artificial subsurface barrier to prevent sea-water intrusion is not considered feasible. Employment of a pumping trough parallel to the coast is also not considered feasible in this area.

Oxnard Plain Basin

The most feasible method for halting sea-water intrusion in the Oxnard Plain Basin would require reduction of ground water extractions to the safe yield of the basin, which could be increased to some extent by artificial recharge in forebay areas. Supplemental water requirements would be obtained from existing and proposed surface storage facilities in the Santa Clara River watershed.

Artificial recharge in the forebay areas, combined with use of a surface distribution system on the Oxnard Plain, could also be utilized in conjunction with a pressure ridge along the coast, or subsurface cutoff walls. Injection through wells would be required to create a pressure ridge. Under these conditions, pressure levels underlying the plain inland from the barriers could be lowered below sea level without inducing intrusion of sea water.

The Oxnard Plain is bordered by about 17 miles of coast line and is underlain with Recent alluvium and Upper Pleistocene deposits 200 feet or more in thickness. Installation of artificial subsurface barriers to depths of 200 feet may be feasible. Since sea-water intrusion has been observed only in the Port Hueneme and Point Mugu areas, which coincide with the locations of the Hueneme and Mugu submarine canyons, respectively, it may be that sea-water intrusion controls are only needed in these areas. It is likely that aquifers are not in hydraulic continuity with the ocean elsewhere along the coast. At any rate, if a subsurface barrier or a pressure ridge were employed in an attempt to protect the Oxnard Plain from further intrusion, they should first be constructed at the aforementioned two critical areas.

Direct recharge of local, or future imported, supplies in the forebay areas supplying ground water to the Oxnard Plain Basin does not, in itself, appear to be a complete solution to the sea-water intrusion problem, due principally to the inadequate transmissibility of the pressure aquifers. In other words, ground water forebay storage could be full, while pressure levels underlying the Oxnard Plain were below sea level.

Development of a pumping trough parallel to the coast to prevent intrusion into the aquifers underlying the Oxnard Plain does not appear to be feasible.

In 1955, the United Water Conservation District completed construction of Santa Felicia Dam on Piru Creek, capable of impounding 100,000 acre-feet of water. This project is being operated in conjunction with an artificial recharge project in Piru Basin and two recharge projects in the Oxnard Forebay Basin. Water from this project is supplied to the Oxnard Plain through a distribution system, now partially completed. Water development projects are discussed in State Water Resources Board Bulletin No. 12, "Ventura County Investigation," October, 1953.

West Coast Basin

From data presently available, it appears that the most feasible plan for prevention of sea-water intrusion in the West Coast Basin, Los Angeles County, consists of a combination of reduction of pumping draft and artificial recharge in forebay and coastal areas. In addition, a change in the pumping pattern, i.e., reducing ground water withdrawals along the coast in favor of increased pumping further inland, would tend to decrease the landward hydraulic gradient and retard the intrusion rate.

The base of the main water-bearing zone, the merged Silverado formation, is as much as 500 feet below sea level along the coast of Santa Monica Bay. This formation may also be in hydraulic continuity with San Pedro Bay, but its depth in this region is unknown. The depth of this formation along most of the coast line tends to preclude the use of an artificial subsurface barrier to prevent further intrusion. Sea water is known to have intruded from San Pedro Bay into the Gaspur zone, which overlies a small portion of the Silverado formation, but production from this zone is relatively small compared to that from the Silverado formation, therefore large expenditures of funds for facilities to prevent intrusion into the Gaspur zone might not be justified.

Unless an industrial demand for large quantities of brackish water should develop, the use of a pumping trough adjacent to the coast to prevent intrusion does not appear to be feasible.

As discussed in Chapter V, the Los Angeles County Flood Control District has injected softened Colorado River water through wells in the Manhattan Beach-Hermosa Beach area on an experimental basis since February, 1953. It has thereby demonstrated that it is possible to maintain a pressure ridge above sea level along a one-mile reach of coast for long periods of time. Economic feasibility of such a ridge depends largely on the cost of recharge water. Two sources of water are presently being considered for this project. One possible supply is sewage effluent from the nearby City of Los Angeles' Hyperion treatment plant, which now discharges to the ocean through an outfall sewer. The second source under consideration is untreated Colorado River water, which is available from the Metropolitan Water District of Southern California, though at a considerable distance from the project.

The Los Angeles County Flood Control District has recently launched a geologic and hydrologic study of various plans for prevention of sea-water intrusion. These plans could be incorporated into the operations of a proposed replenishment district covering the West Coast Basin and portions of the Central Basin, to be formed under provisions of the Water Replenishment District Act. The replenishment district would obtain funds, through taxes or an assessment on ground water pumping, to purchase imported or reclaimed waters for artificial recharge. In this manner, it is hoped to prevent further intrusion and permit continued utilization of the ground water basins.

As stated heretofore, the plan for prevention of sea-water intrusion in the West Coast Basin which appears to be the most feasible incorporates a combination of several methods of control. Features of the plan include extending the existing pressure ridge project to a total length of about 11 miles along Santa Monica Bay; installation of an injection well and/or spreading project near Alamitos Bay and near Wilmington to protect the Silverado formation and possibly the Gaspur zone; spreading of runoff, imported water, and possibly reclaimed water in the Montebello Forebay Area; reduction of ground water withdrawals in the West Coast Basin and in the Central Basin; and additional use of imported surface supplies. A plan incorporating these features is depicted on Plate 31. The Los Angeles County Flood Control District has estimated from preliminary data that the cost of installing fresh-water ridges along Santa Monica Bay, near Wilmington, and near Alamitos Bay would be in the order of $7,600,000.

East Coastal Plain Pressure Area

The most feasible plan for preventing encroachment of sea water into the East Coastal Plain Pressure Area of Orange County appears to include the following elements: increased use of imported or other sources of supplemental supplies by surface distribution, reduction of pumping draft in the coastal portion of the plain, rearrangement of pumping draft, and an expanded program of artificial recharge in forebay areas. The success of such an approach depends largely on the ability of aquifers to transmit water from forebay areas to points of use on the coastal plain.

Like the West Coast Basin, there is an imported supply of water available to most major ground water producers in the East Coastal Plain Pressure Area, provided through the Orange County and Coastal Municipal Water Districts from the Metropolitan Water District of Southern California. Thus, it is likely that a voluntary reduction of ground water withdrawals along the coastal margin of the coastal plain could be effected, especially when existing well installations and pumping equipment required replacement.

Although about three-fourths of the 16-mile coast line are open to the ocean, sea water has intruded to an appreciable degree only into the Talbert water-bearing zone in the Santa Ana gap. As previously mentioned, the Newport-Inglewood uplift impedes, wholly or in part, the landward intrusion of sea water into the deeper Pleistocene and Tertiary sediments along the coast.

The Talbert zone is exposed to the ocean along about three miles of coast, and its base is approximately 190 feet below land surface. Construction of an artificial subsurface barrier across the Santa Ana gap to prevent further intrusion might prove feasible.

Geologic data available indicates that a fresh-water ridge across the Santa Ana gap might also prevent further intrusion into the Talbert zone. One possible source of water for such a project is the sewage effluent which now discharges to the ocean through the nearby Orange County Sanitation District's outfall sewer.

Unless an industrial demand for large quantities of brackish water develops, use of a pumping trough adjacent to the coast to prevent sea-water intrusion does not appear feasible.

Spreading of storm runoff in the forebay areas of the coastal plain, which has been conducted since the early 1900's, has been instrumental in slowing the rate of decline of ground water levels. In 1953, the Orange County Water District was formed for the purpose of replenishing ground water supplies by artificial recharge. Funds for purchase of water are obtained through assessments on ground water extractions. The present assessment is $3.90 per acre-foot of water pumped. Up to July 31, 1958, the district has purchased a total of approximately 420,000 acre-feet of untreated Colorado River water from the Metropolitan Water District of Southern California. This water has been allowed to percolate in the channel of the Santa Ana River and in off-channel artificial recharge basins in the Santa Ana Forebay Area.

The Orange County Water District is currently constructing additional spreading basins and expanding conveyance facilities to supply its artificial recharge projects, existing and proposed. The District also conducts annual studies to determine the amount of Colorado River water required to satisfy the imbalance between ground water discharge and recharge.

The Talbert Water District, formed in 1954, is diverting approximately 2,200 acre-feet of primary effluent annually from the Orange County Sanitation District's outfall sewer. This effluent is being utilized for irrigation purposes on 2,250 acres of land in the Santa Ana gap. As of 1957, most of the area of the Water District was affected by sea-water intrusion and many wells had been abandoned. Utilization of this effluent has reduced pumping draft on the basin, and thus been instrumental in retarding the advance of sea-water intrusion.

Mission Basin

Mission Basin in San Diego County is considered one of the few ideal locations in the State for construction of an artificial subsurface barrier to prevent sea-water intrusion. Construction of a puddled clay cutoff wall at this site is considered physically feasible, since the base of the unconsolidated alluvium is about 200 feet below land surface and only about a thousand feet of basin are open to the ocean. A cutoff wall across the mouth of the San Luis Rey River would stop subsurface outflow and natural aquifer flushing in Mission Basin, the coastal portion of the valley. Despite this lack of subsurface outflow, however, favorable salt balance conditions would probably be maintained if present exportation of ground water continued.

The use of a fresh-water mound across the mouth of the valley to prevent intrusion might also be suitable here, due to the short reach of coast involved. Sewage effluent from the City of Oceanside's treatment facilities or imported Colorado River water might serve, wholly or in part, as a water supply for such a water mound. Colorado River water is now delivered to the City of Oceanside, via San Luis Rey Valley, through the Fallbrook-Oceanside Branch of the San Diego Aqueduct. Construction of a second aqueduct to supply additional Colorado River water to San Diego County is in progress and will augment the present imported supply to San Luis Rey Valley.

The development of a pumping trough across the mouth of the San Luis Rey River also appears possible. Gravel washing operations in this area utilize saline ground waters at present, and could conceivably use ground water extracted in connection with a pumping trough. This method of solution does offer the distinct advantage of contributing to maintenance of favorable salt balance, although this factor of itself does not justify its adoption.

If imported water were used directly as a surface supply, in conjunction with reduction of ground water use and spreading to recharge the overdrawn coastal basin, ground water levels could probably be raised above sea level. Intrusion would thus be halted, although complete utilization of the ground water basin would not be achieved, with resultant waste of local runoff. With regard to decreasing ground water withdrawals, a suit has been filed to adjudicate the water rights of the valley.

On June 2, 1957, voters of the City of Oceanside authorized a bond issue to finance reclamation of sewage effluent. As a result of this bond issue, the City has abandoned its outfall sewer to the Pacific Ocean, and constructed a line to carry treated sewage to Whalen Lake in Mission Basin. Effluent from the lake, which serves as an oxidation pond, is spread to recharge ground waters of Mission Basin. The system was placed in operation on July 1, 1958; and the volume of reclaimed sewage will vary from 1,600 acre-feet per year initially to 4,700 acre-feet annually by the year 2000.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

As a result of experiments and investigations authorized by Chapter 1500, Statutes of 1951, and Section 229 of the Water Code, it is concluded that:

1. Ground water reservoirs in California are of tremendous economic importance to the State as basic sources of water supply, as reservoirs for regulation of local runoff and imported supplemental supplies, and as sources of water in time of national emergency.

2. Geologic evidence indicates that water-bearing deposits within many coastal ground water basins are in direct contact with sea water or brackish tidal waters.

3. Sea-water intrusion into coastal ground water basins is a serious threat to ground water quality and the storage capacity of these ground water reservoirs.

4. Restoration of a ground water basin that has been damaged by sea-water intrusion is a slow, difficult, and expensive operation. Prevention is unquestionably the most logical and economical approach to the problem of sea-water intrusion.

5. There is definite evidence of sea-water intrusion in 9 coastal ground water basins of California. Sea water has advanced inland up to 4½ miles in some areas. Continued pumping at present rates will allow further encroachment into these basins, resulting in further widespread deterioration of ground water supplies unless effective remedial measures are undertaken. Damage to the ground water resources of some of these basins is already severe.

6. There are 71 coastal ground water basins in which chloride content of ground waters exceeds 100 parts per million, but the source of degradation is not established. It is suspected that sea-water intrusion is occurring in some of these basins.

7. There are 48 coastal ground water basins in which there is now some development of ground water, and in which sea-water intrusion may become a problem if development exceeds safe yield. There apparently is no sea-water intrusion at present.

8. There are 134 coastal ground water basins in which there is little or no present development of ground water, and little or no information is available regarding hydrologic or water quality conditions. The status of sea-water intrusion in these basins is unknown.

9. Prevention and/or abatment of sea-water intrusion into coastal ground water basins may be accomplished by various methods, depending upon geologic and hydrologic conditions. Five such methods are listed:

a. Raising of ground water levels to or above sea level by reduction in extractions and/or rearrangement of areal pattern of pumping draft;
b. Direct recharge of overdrawn aquifers to maintain ground water levels at or above sea level;
c. Maintenance of a fresh-water ridge above sea level along the coast;
d. Construction of artificial subsurface barriers;
e. Development of a pumping trough along the coast.

10. Cost comparisons of control methods, based on a hypothetical situation, indicated that "raising of ground water levels to or above sea level by reduction in extractions and/or rearrangement of areal pattern of pumping draft" required minimum capital outlay; while lowest operation, maintenance, and water costs were associated with "maintenance of a fresh-water ridge above sea level along the coast." The cost and quality of available supplemental water supplies for direct distribution and/or ground water recharge may be the controlling factor in final determination of the optimum method of control of sea-water intrusion into a coastal ground water basin.

11. Decision as to the method of control to be used at any given location should be based upon thorough study of geologic, hydrologic, and water quality data, and an appraisal of pertinent engineering, legal, and economic aspects.

12. Any comprehensive program for abatement of sea-water intrusion should include establishment and enforcement of suitable standards of well construction and abandonment to prevent degradation of ground waters by interconnection between water-bearing zones.

13. Principal conclusions drawn from laboratory model studies of sea-water intrusion into a confined aquifer, conducted by the Sanitary Engineering Research Laboratory, University of California, Berkeley, are as follows:

a. In accordance with the Ghyben-Herzberg principle, the fresh-water piezometric surface must be maintained above sea level a distance equal to $(S-1)$ times the distance below sea level of the lowest point within the aquifer which must be protected from sea-water intrusion, where S is the specific gravity of sea water.

b. When a pressure ridge is maintained above sea level, the fresh-water flow seaward is inversely proportional to the length of the sea water wedge from the ocean outlet, as determined by the following equation:

$$Q = \tfrac{1}{2}(S-1)\frac{MT}{L}$$

Where

$Q =$ seaward fresh-water flow per foot of ocean front.

$S =$ specific gravity of sea water.

$M =$ thickness of aquifer, down to the lowest depth which must be protected.

$T =$ aquifer transmissibility for 100 per cent hydraulic gradient.

$L =$ length of sea-water wedge, from ocean outlet to the toe.

Fresh-water waste to the ocean is independent of the elevation of the aquifer.

c. The total injection rate along the recharge line must equal the sum of fresh-water waste to the ocean necessary to maintain the position of the sea-water wedge and the overdraft of the basin originally being satisfied by landward flow of sea water

d. When conditions are such that the saline wedge moves inland, the wedge tends to flatten out and the toe moves somewhat faster than the remaining interface. In a prototype aquifer, it is believed that nonuniformity of material, with accompanying varying transmissibility, may greatly distort the shape of the interface since the intruding saline water will tend to follow the path of least resistance.

e. Where a recharge line is located in an area where sea water has already intruded into an aquifer, the sea-water wedge will be divided as a result of injection and saline water will be displaced both seaward and landward. Injected fresh water tends to override the severed toe, which becomes flatter as it continues to move inland.

f. Injection well spacing is of little importance, except that the toe of the intruded wedge should be held at least half a well spacing seaward from the injection line.

g. Intruding sea water can be intercepted by establishment of a pumping trough, created by a line of pumping wells parallel to the coast. This method would provide no replenishment to a coastal basin, but the loss of fresh water need be no greater than that which would occur with a pressure ridge established through the use of injection wells.

14. Laboratory studies by the University of California at Berkeley upon the effectiveness of admixtures in reducing aquifer permeability may be summarized as follows:

a. Bentonite slurry stiff enough to adequately reduce the permeability of an aquifer would probably be too stiff to use with ordinary excavation equipment. Stiffer slurries containing 7 to 8 per cent dry bentonite are effective in permeability reduction in well-graded backfill mixtures containing 25 to 30 per cent silt.

b. Preliminary data indicate that the permeability to sea water of a mixture containing bentonite slurry is roughly ten times its permeability to fresh water.

c. None of the admixtures tested, including bentonite, bentonite with asphalt emulsion, bentonite with portland cement, and chrome-lignin, provide a complete seal.

15. The West Coast Basin Experimental Project established conclusively that water can be successfully injected into a coastal confined aquifer on a continuous basis. The results of this research program, which are applicable to areas having similar geologic and hydrologic conditions, may be summarized as follows:

a. Injection of water through wells can pressurize a confined aquifer continually along a coastal reach, thereby reversing any pre-existing landward gradient and preventing further sea-water intrusion.

b. Loss of fresh water to the ocean will be small in relation to the total quantity of water injected.

c. An aquifer containing water already degraded by sea-water intrusion can be made usable by injection of water through wells.

d. Wells used for injection of water into a confined aquifer must be properly sealed at the confining member and carefully developed. Gravel-packed wells proved most successful on this project.

e. A recharge rate of six second-feet per mile, effected by injection through wells spaced 500 feet apart, is adequate to establish a pressure ridge two to three feet above sea level. This is sufficient to halt the inland flow of sea water.

f. Water for injection must be compatible chemically with native waters and must be treated to avoid clogging the aquifer. Chlorine dosages of between five and ten parts per million are necessary to prevent slime growth and maintain transmissibility.

16. Laboratory tests conducted by the University of California at Los Angeles indicate that pretreatment of injection water (softened Colorado River water) with chlorine plus acid is most effective for

maintaining permeability of the formation (Silverado water-bearing zone).

17. Water quality studies conducted by the United States Geological Survey, Quality of Water Branch, confirm the fact that salinity in the confined Silverado water-bearing zone of the West Coast Basin is caused by intruding sea water and not oil well brines.

18. Preliminary field tests by the Los Angeles County Flood Control District indicate that sewage effluent from the City of Los Angeles' Hyperion treatment plant can be successfully injected through wells in the West Coast Basin, after treatment by further oxidation, settling, filtration, and chlorination.

19. Serious economic losses can accrue to urban and agricultural communities overlying ground water basins subject to or threatened by sea-water intrusion. These losses are largely associated with the impairment of the basin as an underground reservoir and as a source of water supply. Evaluation of these losses is essential in determining the feasibility of plans for protecting, replacing, or augmenting the required supply.

20. In order to effectively control or prevent sea-water intrusion, authority is required for the planned management of threatened ground water basins; and an efficient method for the determination of rights to the use of ground water is necessary. Existing laws are not fully adequate for these purposes.

RECOMMENDATIONS

In order to promptly detect sea-water intrusion, to better predict rates of intrusion, and to effectively control and prevent sea-water intrusion, it is recommended that the following measures be undertaken in all coastal ground water basins:

1. There should be a continuous program for collection and intepretation of hydrologic, geologic, and water quality data, including drilling of test wells as required.

2. Improved methods of detecting sea-water intrusion and accurately differentiating such intrusion from other possible sources of degradation should be developed.

3. There should be continuing study and preparation of plans for controlling or preventing intrusion in known areas of sea-water intrusion.

4. Communities confronted with the problem of sea-water intrusion should evaluate the economic and related impacts of available alternatives prior to adoption of a course of action.

5. After thorough study and consultation with interested parties throughout the State, legislation should be prepared to strengthen and clarify the authority for planned utilization of ground water basins, and to improve existing procedures for the determination of rights to the use of ground water.

6. It is essential that positive measures be initiated as soon as possible to halt and abate sea-water intrusion in all basins known to be affected at present, and to prevent intrusion into threatened areas. Included in these measures should be early formulation and implementation of plans for furnishing additional or substitute water supplies, as required. Where public agencies with adequate powers to accomplish these tasks are not already in existence, formation of such agencies should be started immediately.

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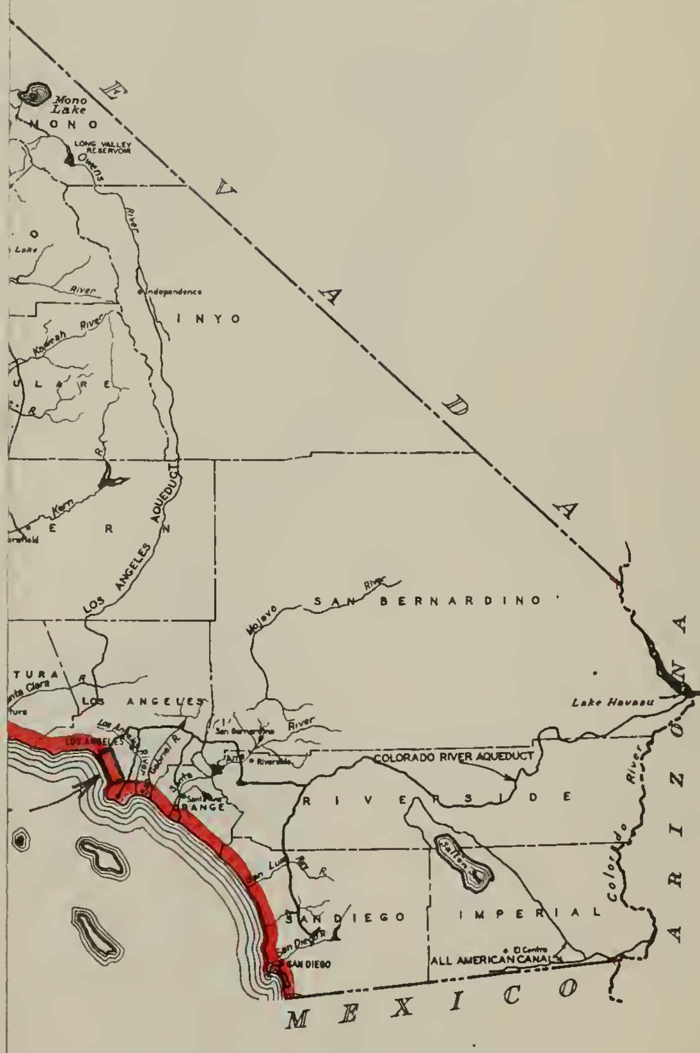
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

LOCATION OF AREA OF INVESTIGATION

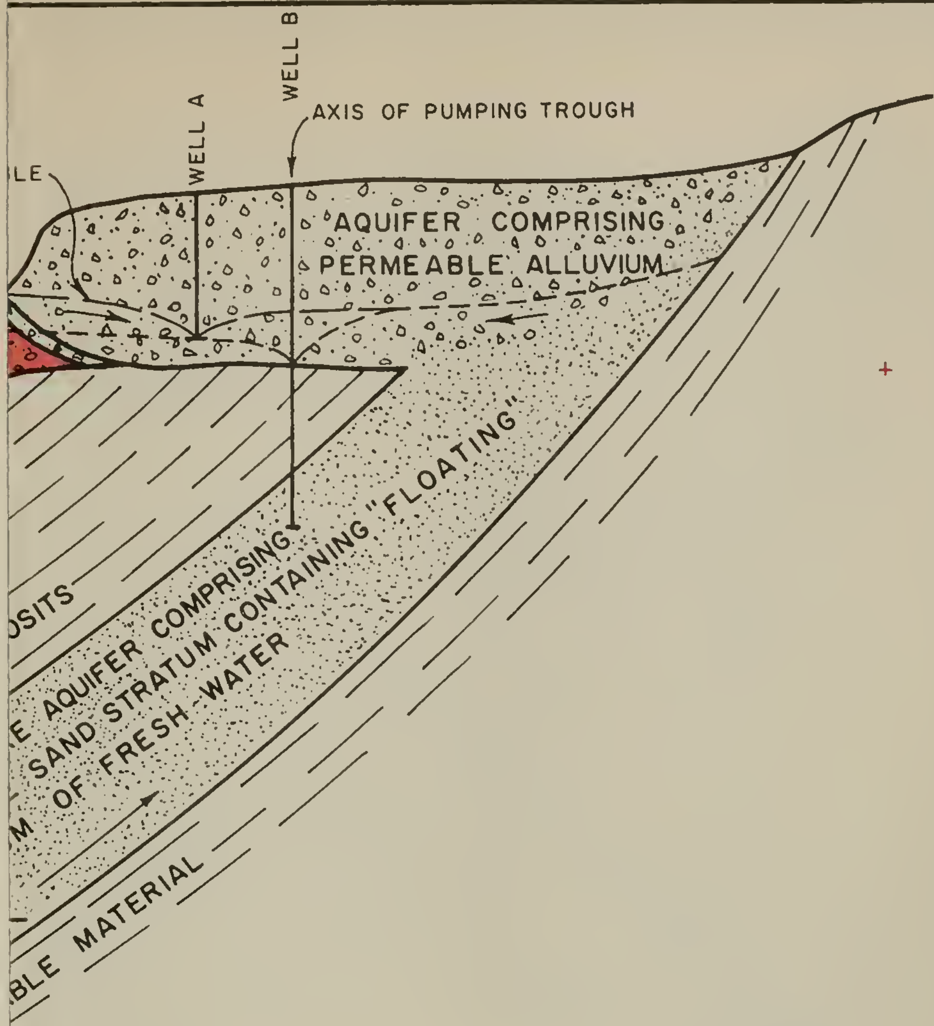
SCALE OF MILES
40 0 40 80



STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

LOCATION OF AREA OF INVESTIGATION

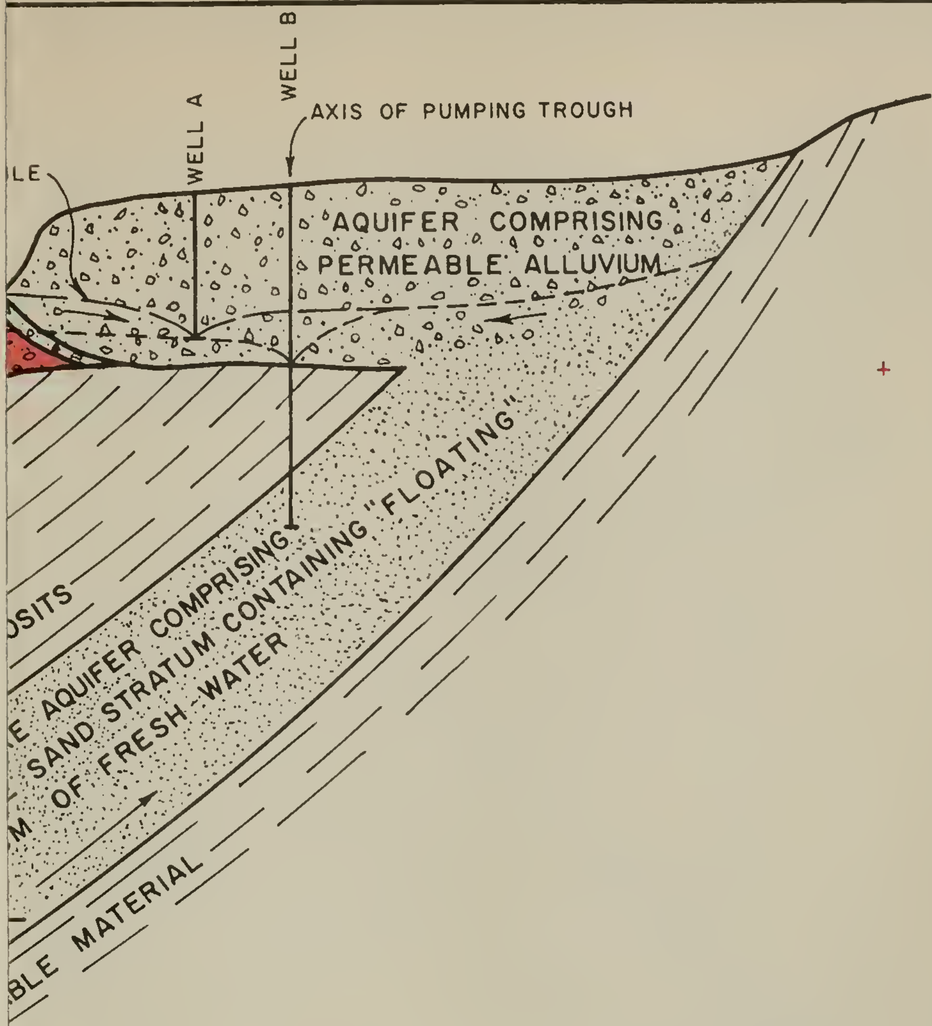


LEGEND

SEA-WATER INTRUSION

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

DIAGRAMMATIC SECTIONS
THROUGH A COASTAL GROUND WATER BASIN

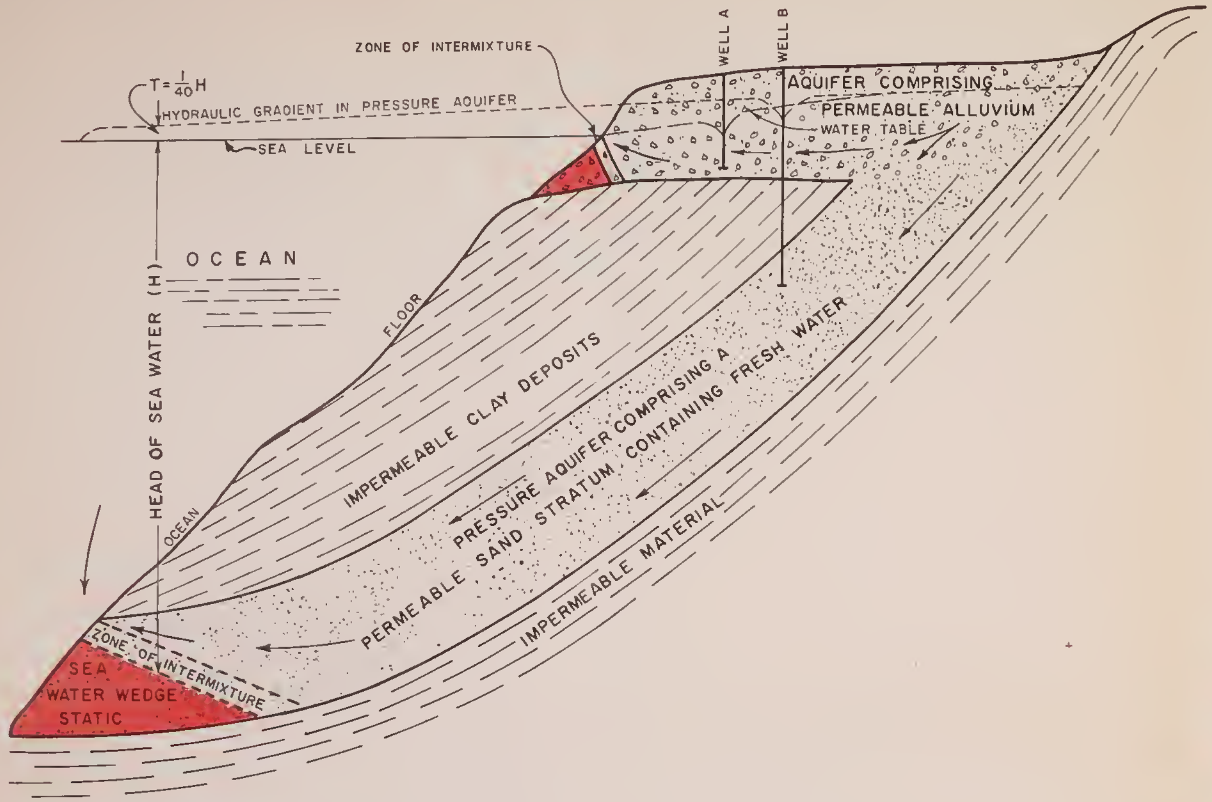


LEGEND

SEA-WATER INTRUSION

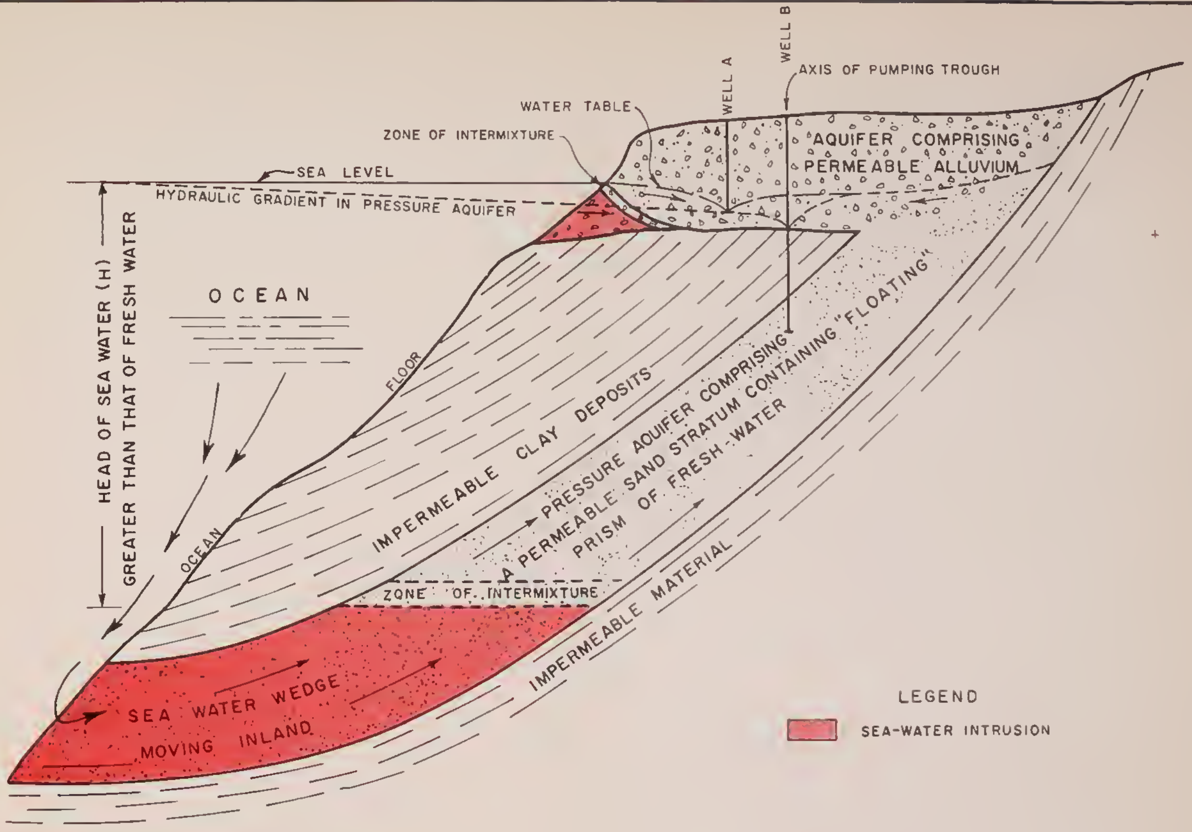
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

DIAGRAMMATIC SECTIONS
THROUGH A COASTAL GROUND WATER BASIN



Condition I (Seaward sloping hydraulic gradient)

Replenishment to the ground water supply exceeds draft on the ground water basin, and as a consequence the water table and pressure gradient slope seaward and fresh water is discharged to the ocean through the aquifers in contact with the ocean floor. Wedges of salt water exist near the points of discharge. The length of these wedges is controlled by the quantity of seaward fresh water flow and the thickness and transmissibility (permeability) of each aquifer. Parameters governing length of wedge and relationship of fresh and sea-water pressure heads are developed in Appendix C.



Condition II (Landward sloping hydraulic gradient)

Draft on the ground water basin exceeds the supply to ground water resulting in a landward slope of the water table and pressure gradient and intrusion of sea water into the aquifers. Since the head of fresh water is less than that of the sea water a condition of instability exists. The prism of fresh water within the deep aquifer is "floating" on sea water. The sea-water wedge will move inland to axis of pumping trough.

LEGEND

SEA-WATER INTRUSION

STATE OF CALIFORNIA
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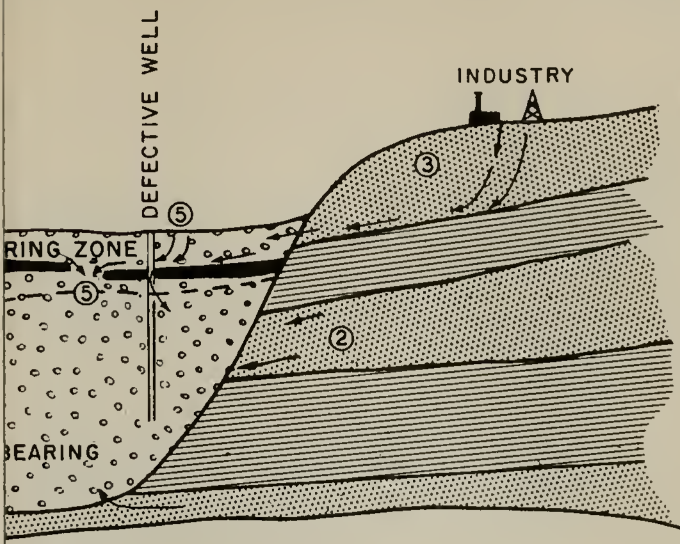
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

DIAGRAMMATIC SECTIONS
THROUGH A COASTAL GROUND WATER BASIN



FILLED GROUND WATER BASIN UNDERLAIN
E SEDIMENTS OF MARINE ORIGIN

END

AND STRATA

IRECTION OF
ROUND WATER
IOVEMENT

through evaporation. The seepage, unconsumed by vegetation, re-
ching salts from the soil.

ligration of Saline Waters

and were subsequently elevated to their present positions. Sea water
the alluvium under influence of the hydraulic gradient created by
migration was generally negligible.

of Sewage and Industrial Wastes

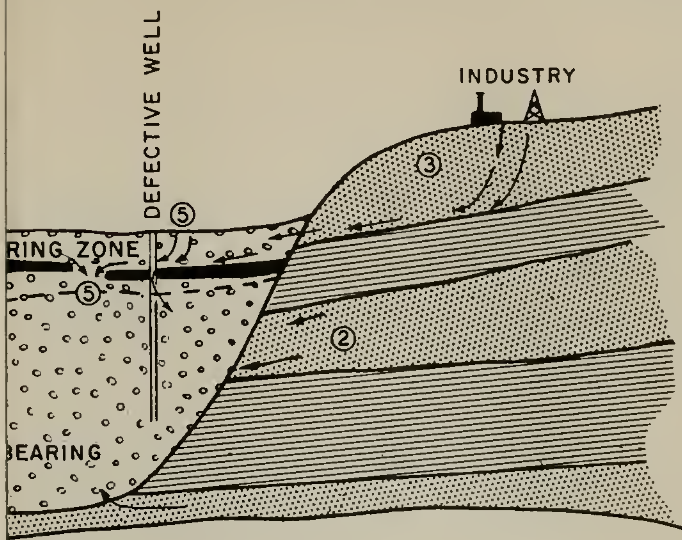
permeable sumps ultimately migrates to the ground water supply.

rface Waters From Streams, Lakes and Lagoons

supply.

nters the lower productive water-bearing zone through an opening
improperly constructed or abandoned wells.

CES OF INCREASED GROUND WATER
THAN SEA-WATER INTRUSION



ILLED GROUND WATER BASIN UNDERLAIN
E SEDIMENTS OF MARINE ORIGIN

END

AND STRATA

IRECTION OF
ROUND WATER
IOVEMENT

through evaporation. The seepage, unconsumed by vegetation, re-
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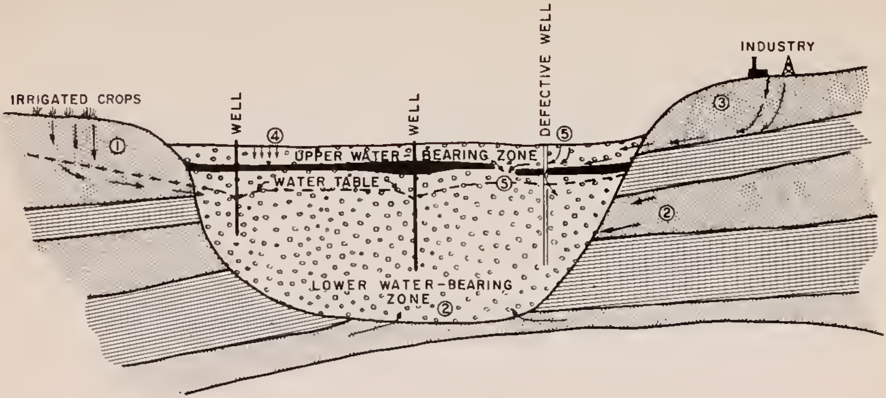
of Sewage and Industrial Wastes
permeable sumps ultimately migrates to the ground water supply.

rface Waters From Streams, Lakes and Lagoons
supply.

nters the lower productive water-bearing zone through an opening
improperly constructed or abandoned wells.

CES OF INCREASED GROUND WATER
HAN SEA-WATER INTRUSION



SCHEMATIC SECTION ACROSS AN ALLUVIUM-FILLED GROUND WATER BASIN UNDERLAIN AND FLANKED BY LESS PERMEABLE SEDIMENTS OF MARINE ORIGIN

LEGEND

ALLUVIUM

CLAY

SHALE

SAND STRATA

DIRECTION OF GROUND WATER MOVEMENT

Key to Illustration

1 ***Degradation of Ground Water Through Use and Re-use***
Example: Irrigation water applied to crops is increased in salinity through evaporation The seepage, unconsumed by vegetation, returns to the ground water and is further degraded en route by leaching salts from the soil.

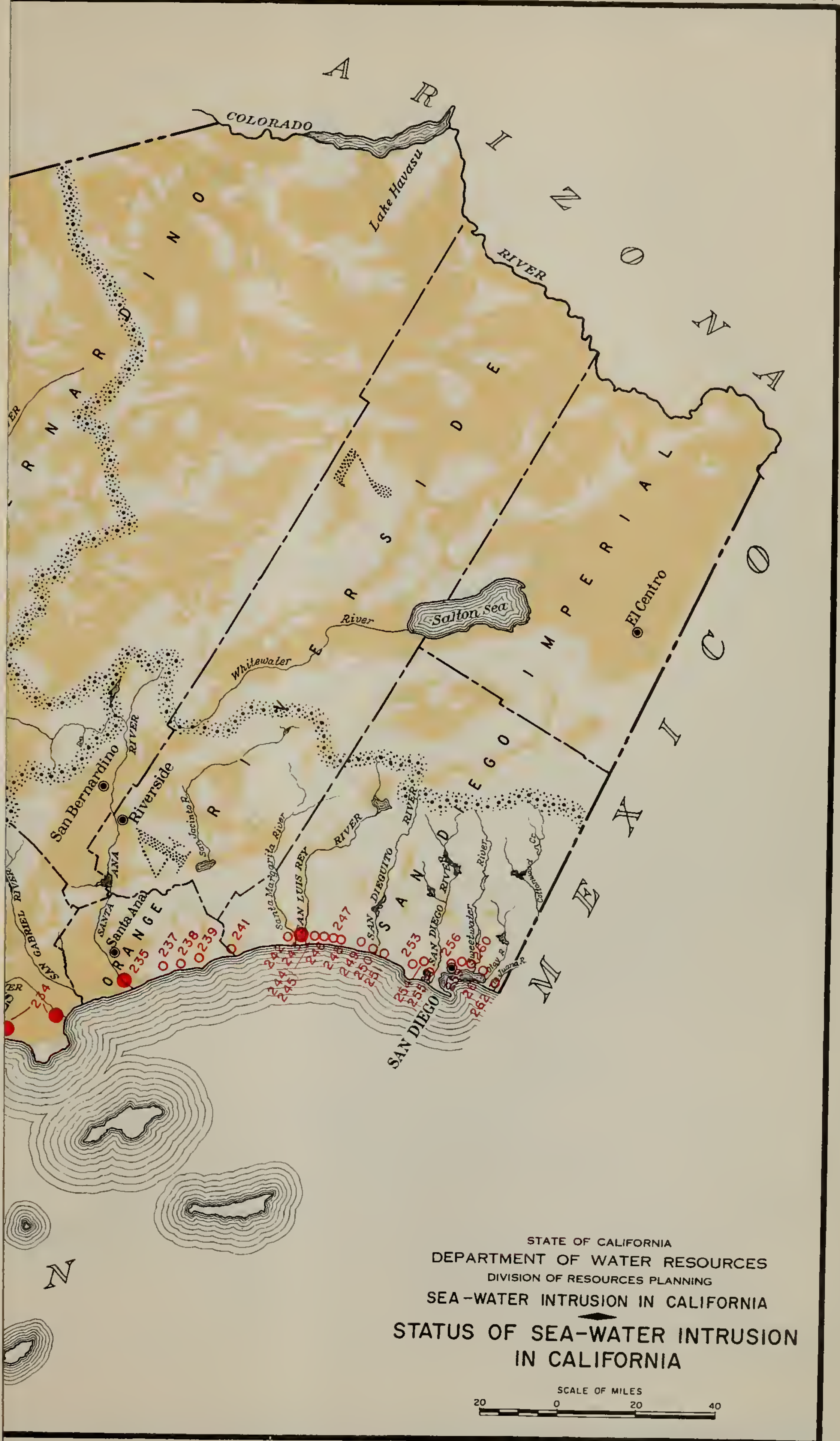
2 ***Degradation of Ground Water Through Lateral or Upward Migration of Saline Waters***
Example· The sand strata illustrated were deposited in the ocean and were subsequently elevated to their present positions. Sea water contained within these sediments since their deposition migrates to the alluvium under influence of the hydraulic gradient created by pumping of the wells. Prior to exploitation of ground water such migration was generally negligible

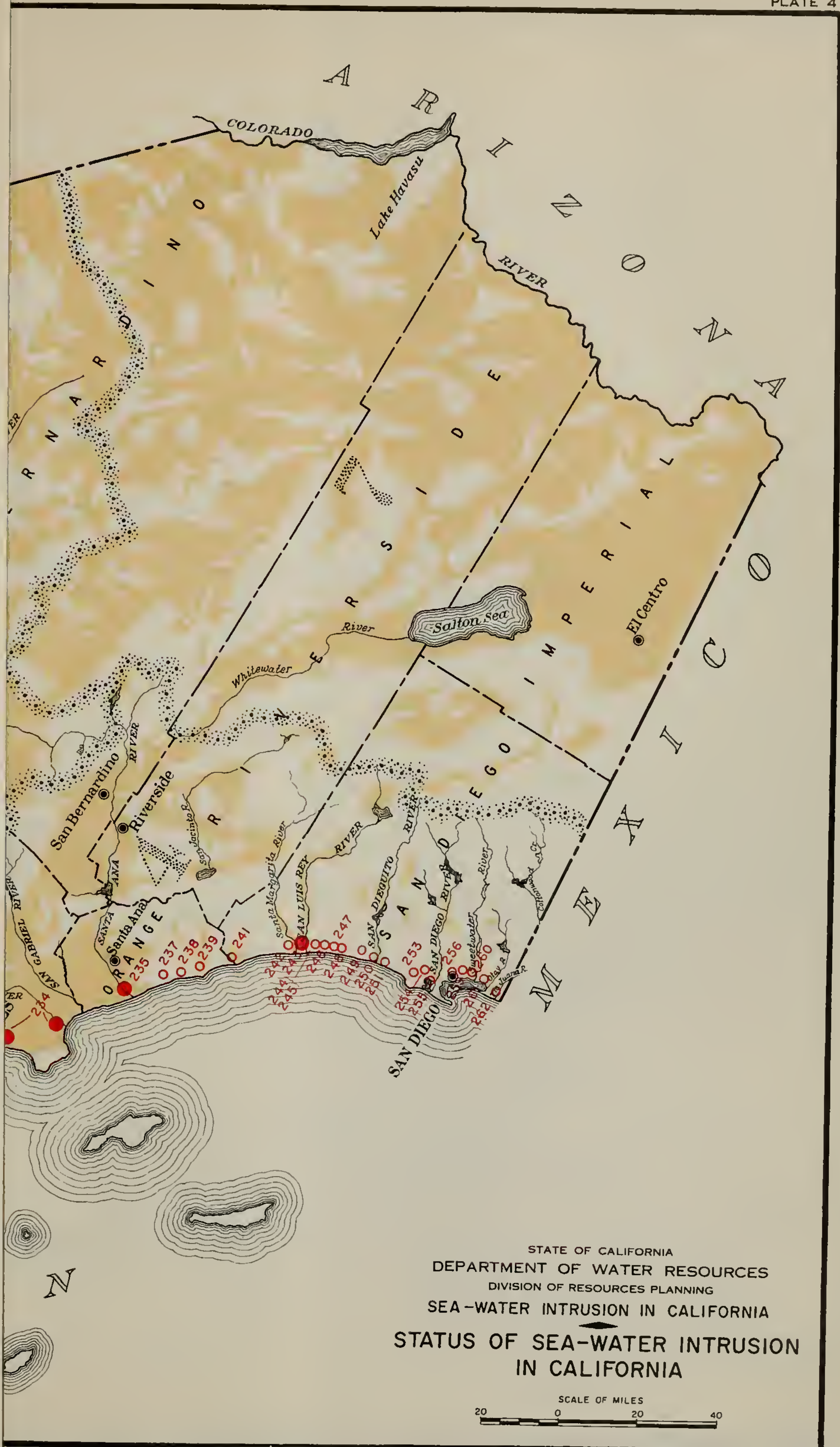
3 ***Degradation of Ground Water Through Downward Seepage of Sewage and Industrial Wastes***
Example: Sewage and industrial waste seeping from cesspools or permeable sumps ultimately migrates to the ground water supply

4 ***Degradation Through Downward Seepage of Mineralized Surface Waters From Streams, Lakes and Lagoons***
Example: Mineralized surface water migrates to the ground water supply

5 ***Degradation Through Interzonal Migration of Saline Waters***
Example: Degraded water within the upper water-bearing zone enters the lower productive water-bearing zone through an opening in the clay layer that separates the two zones or through defective, improperly constructed or abandoned wells.

SCHEMATIC DIAGRAM SHOWING SOURCES OF INCREASED GROUND WATER SALINITY FROM CAUSES OTHER THAN SEA-WATER INTRUSION


ARIZONA
MEXICO
COLORADO
RIVER
Lake Havasu
SAN BERNARDINO
RIVERSIDE
IMPERIAL
SAN DIEGO
ORANGE
Salton Sea
El Centro
Whitewater River
San Bernardino
Riverside
SANTA ANA RIVER
Santa Ana
San Jacinto R.
SAN GABRIEL RIVER
Santa Margarita River
SAN LUIS REY RIVER
SAN DIEGUITO RIVER
SAN DIEGO RIVER
Sweetwater River
Otay R.
Tijuana R.
Cottonwood Cr.
SAN DIEGO
235
237
238
239
241
247
253
256
260
262
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA
STATUS OF SEA-WATER INTRUSION IN CALIFORNIA
SCALE OF MILES
20 0 20 40



STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

STATUS OF SEA-WATER INTRUSION IN CALIFORNIA

SCALE OF MILES
20 0 20 40

INDEX TO GROUND WATER BASINS

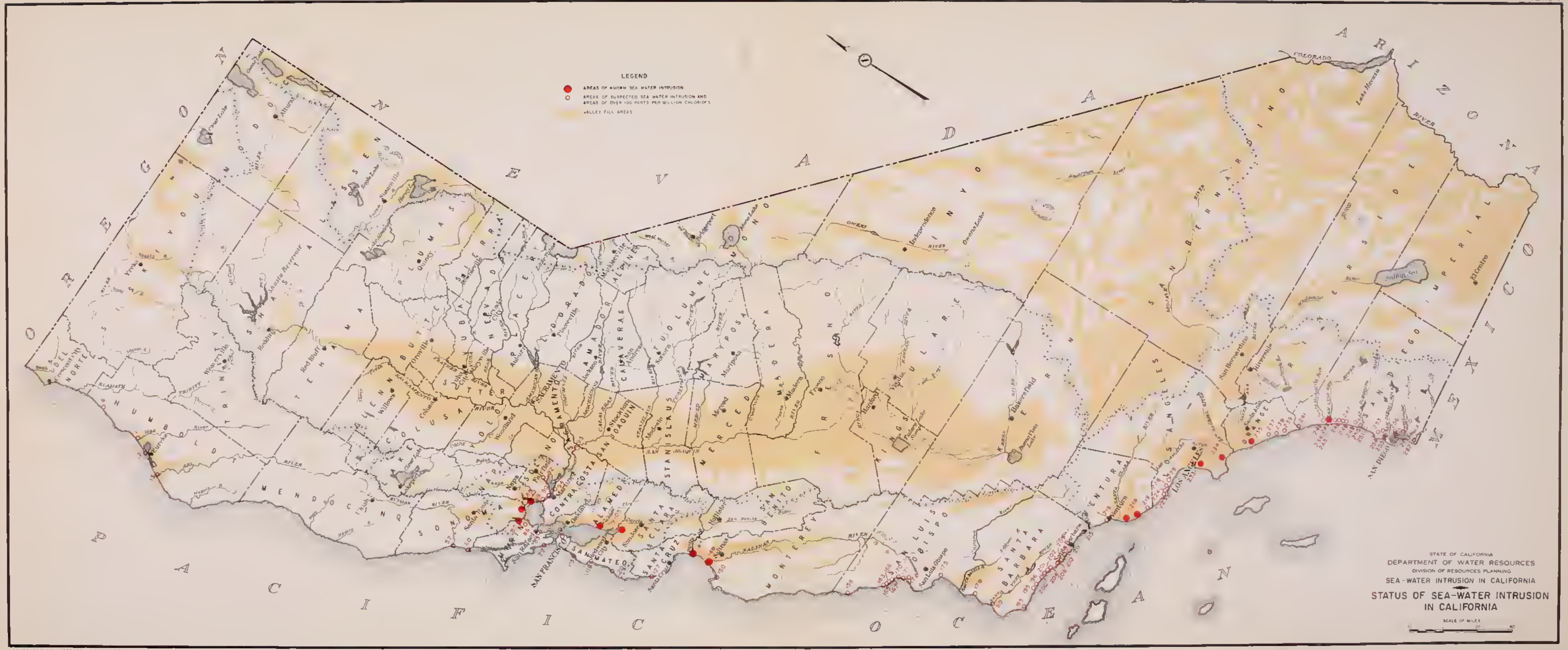
AREAS OF KNOWN SEA WATER INTRUSION

Index No	
*87	Petaluma Valley
88	Napa-Sonoma Valley
105	Santa Clara Valley
147	Pajaro Valley
149	Salinas Valley Pressure Area
218	Oxnard Plain Basin
234	West Coast Basin
235	East Coastal Plain Pressure Area
243	Mission Basin

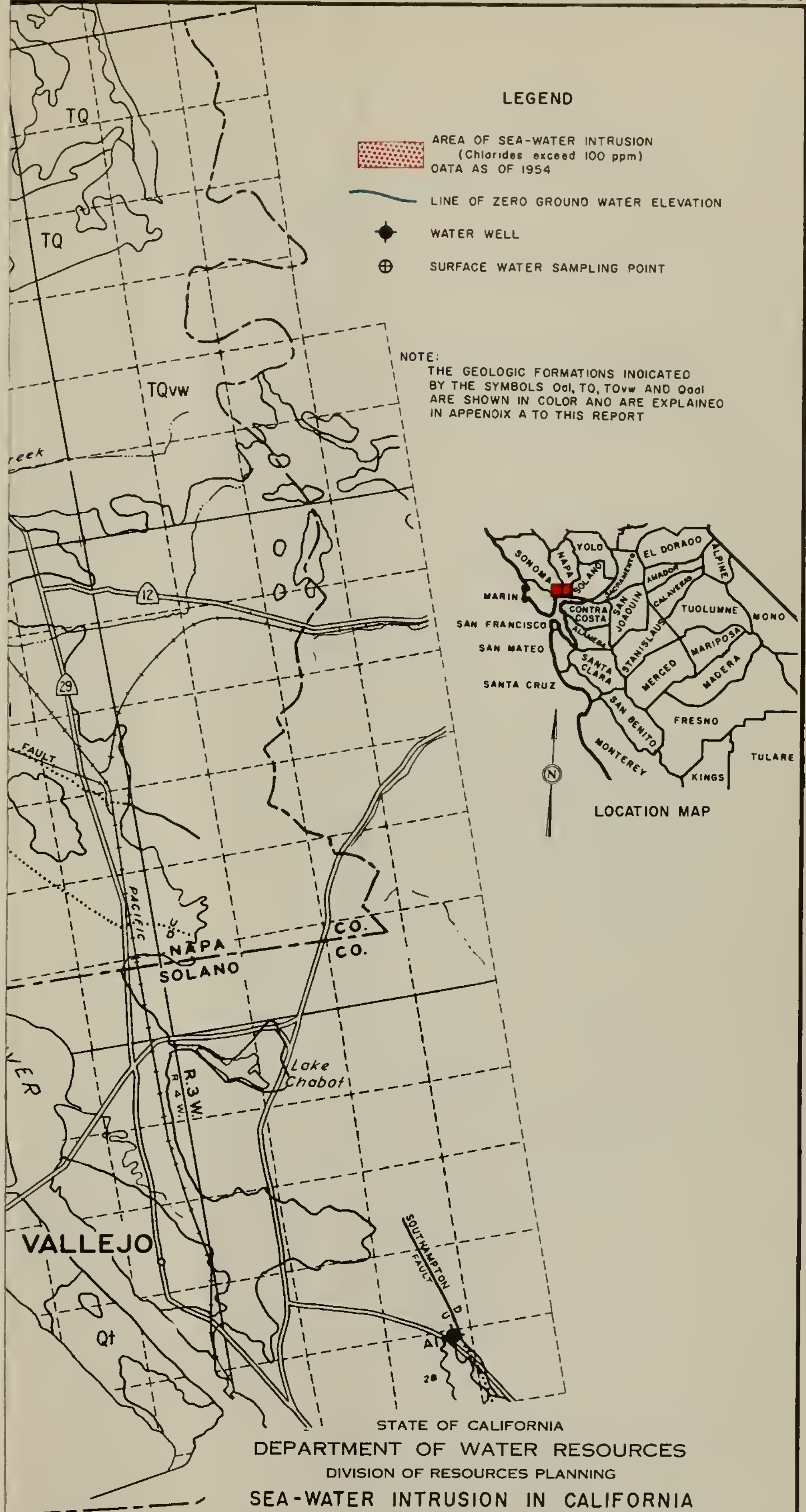
AREAS OF SUSPECTED SEA-WATER INTRUSION AND AREAS OF OVER 100 ppm CHLORIDE

Index No	
6	Redwood Creek Basin
11	Mad River Valley
12	Eureka Plain
13	Eel River Valley
57	Russian River Basin
60	Bodega Bay Basin
77	Frank Creek Basin
83	San Rafael Basin
86	Novato Valley Basin
89	Southampton Bay Basin
90	Benicia Basin
92	Suisun-Fairfield Valley
93	Sacramento-San Joaquin Delta
94	Clayton-Ygnacio Valley
110	Market Street Basin
113	Sharp Park Terrace
118	Halfmoon Bay Terrace
120	San Gregorio Creek Basin
127	Scott Creek Basin
150	Monterey Area
158	Arroyo del Corral Basin
163	Villa Basin
165	Cayucos Point Basin
166	Cayucos Basin
167	Little Cayucos Basin
170	Toro Basin
171	Morro Basin
172	Chorro Basin
175	Pismo Basin
179	Schumann Canyon Basin
180	Lompoc Plain
185	Cojo Basin
195	Gaviota Basin
196	Cementario Basin
200	Tajiguas Basin
201	Canada del Refugio Basin
202	Canada del Corral Basin
204	Las Varas Basin
208	Bell Canyon Basin
209	Campbell Creek Basin
210	Goleta Basin
211	Hope Basin
215	Carpinteria Basin
216	Ventura River Valley
219	Big Sycamore Basin
223	Zuma Canyon Basin
224	Ramera Basin
228	Malibu Basin
229	Las Flores Basin
233	West Coastal Plain-North
237	Laguna Canyon Basin
238	Aliso Basin
239	San Juan Valley
241	San Onofre Valley
242	Santa Margarita Coastal Basin
244	Loma Alta Basin
245	Buena Vista Creek Basin
246	Agua Hedionda Basin
247	Encinas Basin
248	San Marcos Basin
249	San Elijo Basin
250	San Dieguito Valley
251	Soledad Basin
253	Rose Canyon Basin
254	Tecolote Creek Basin
255	Mission Valley Basin
256	Las Chollas Basin
259	Paradise Basin
260	Sweetwater Valley
261	Otay Valley
262	Tia Juana Basin

*Number refers to index number in Appendix A, Table I, Department of Water Resources Publication No. 63, "Sea-Water Intrusion in California"



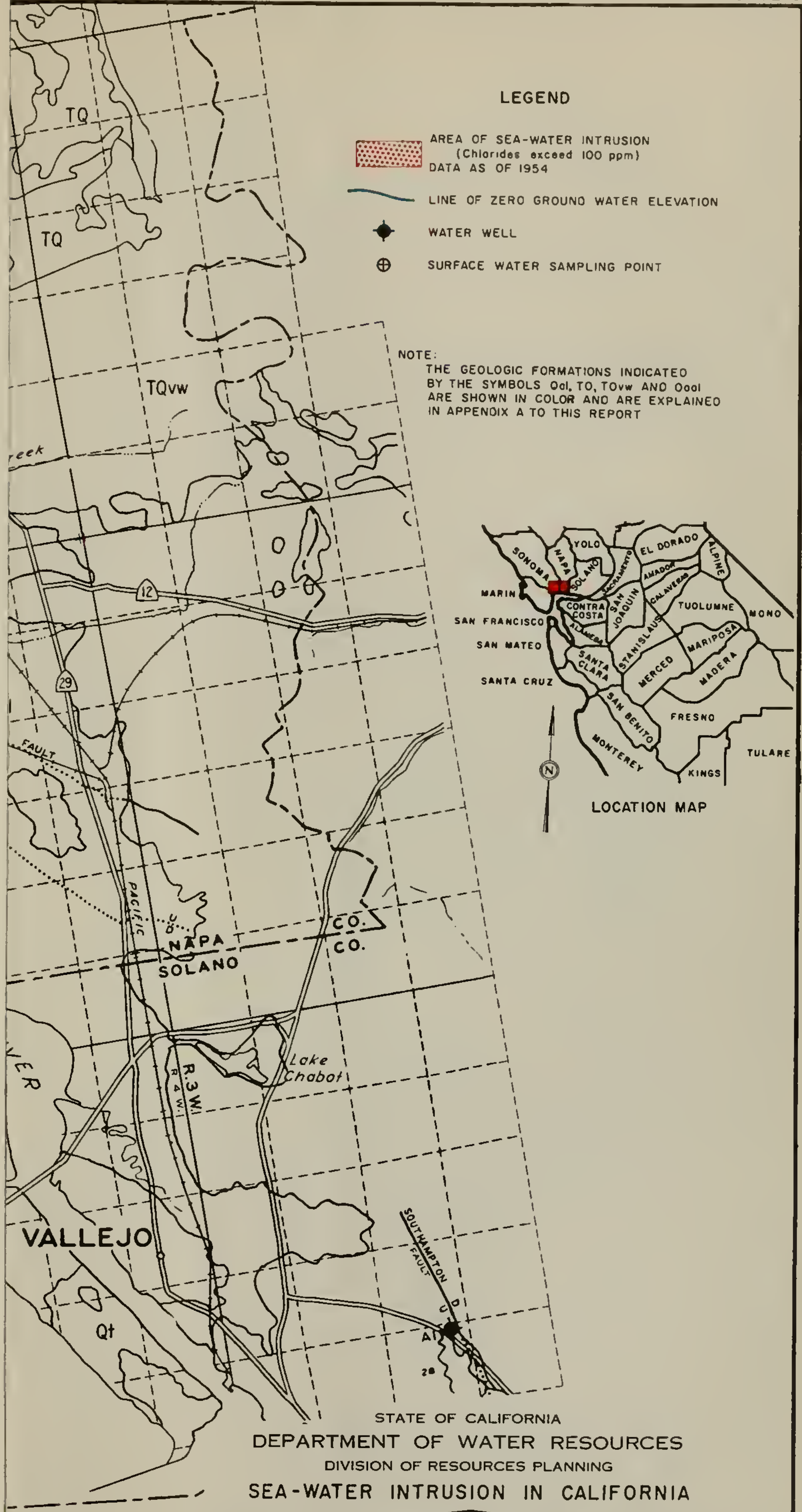
DEPARTMENT OF WATER RESOURCES 1957



STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

STATUS OF SEA-WATER INTRUSION
PETALUMA AND NAPA-SONOMA VALLEYS

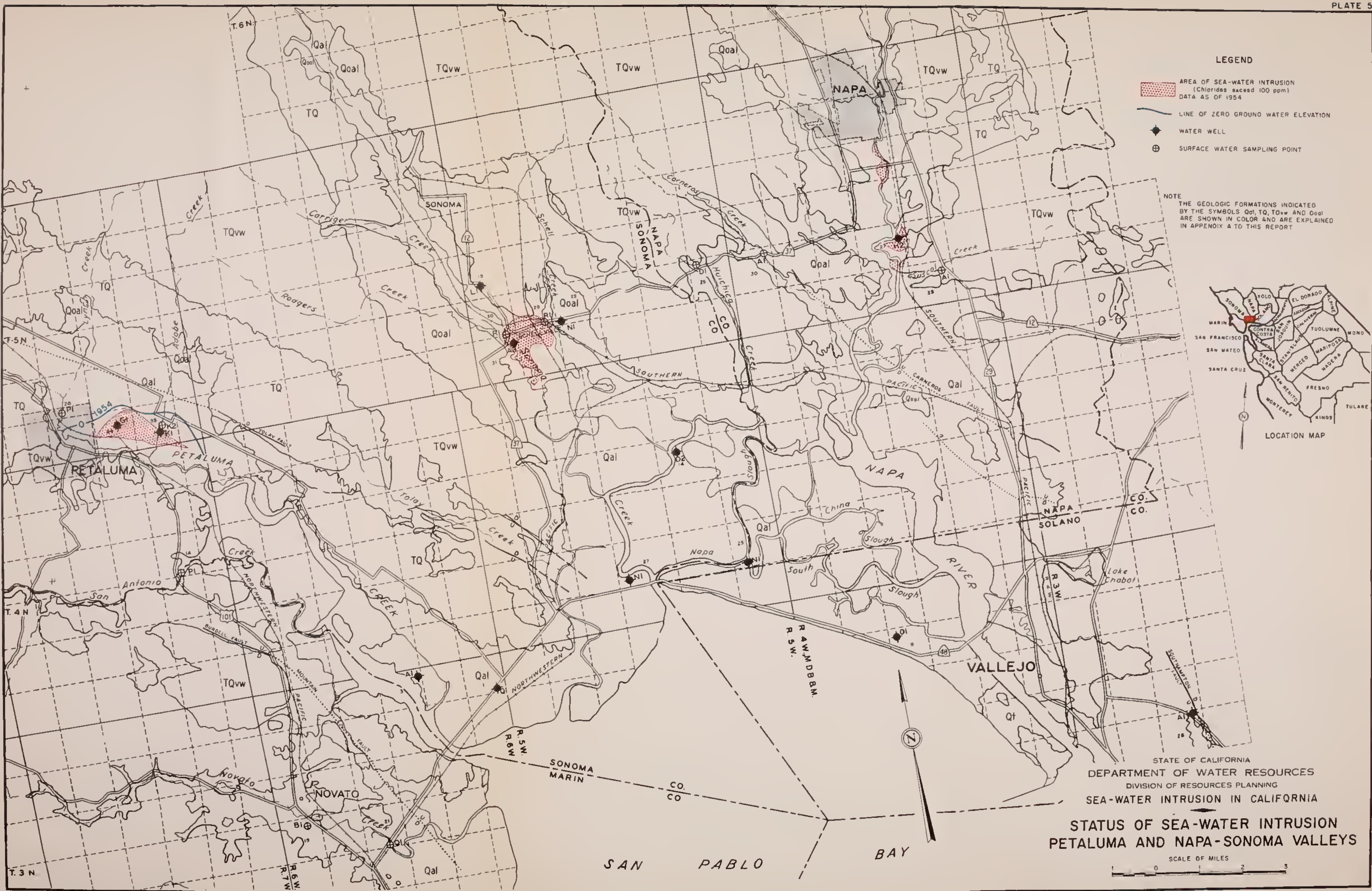
SCALE OF MILES
1 0 1 2 3



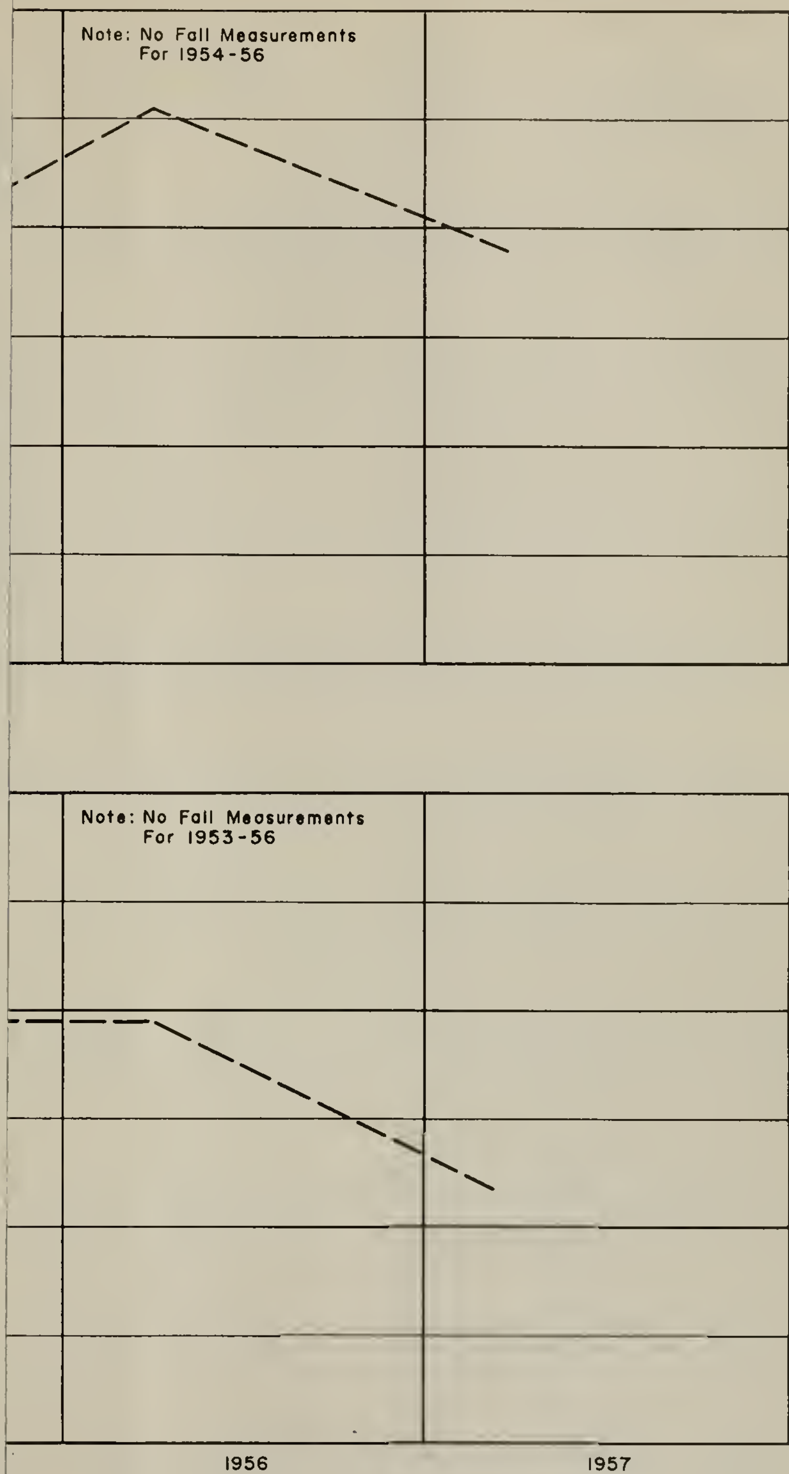
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

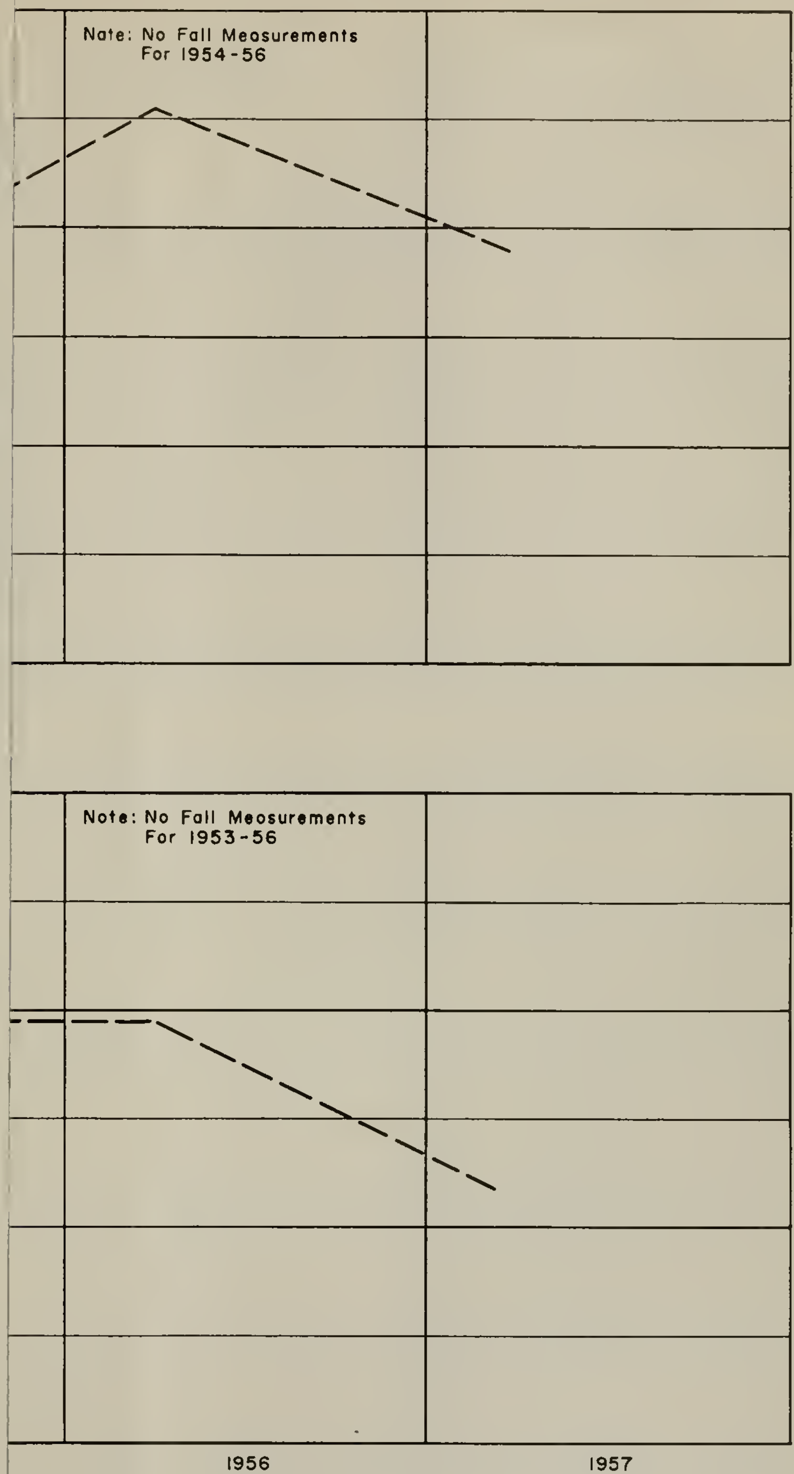
STATUS OF SEA-WATER INTRUSION PETALUMA AND NAPA-SONOMA VALLEYS

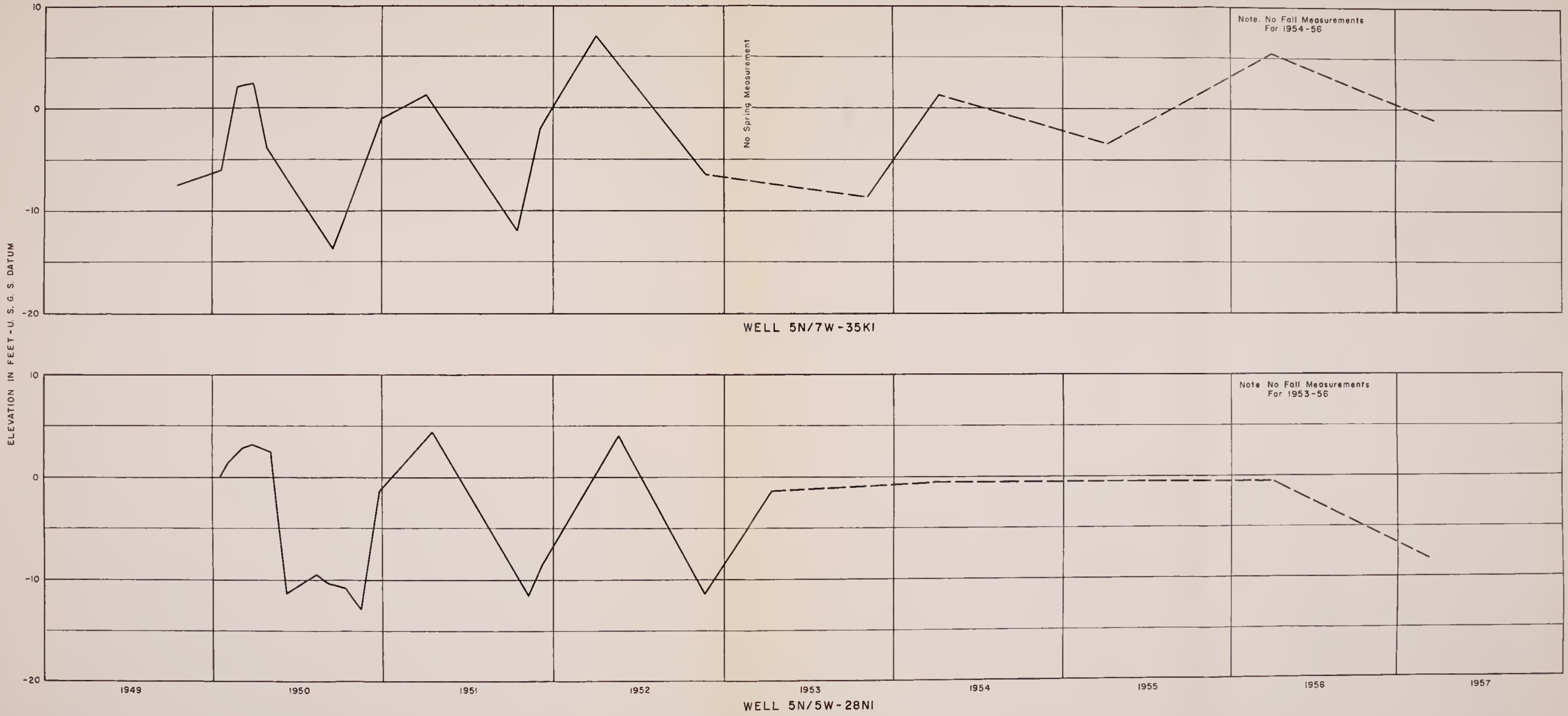
SCALE OF MILES
1 0 1 2 3



DEPARTMENT OF WATER RESOURCES 1957

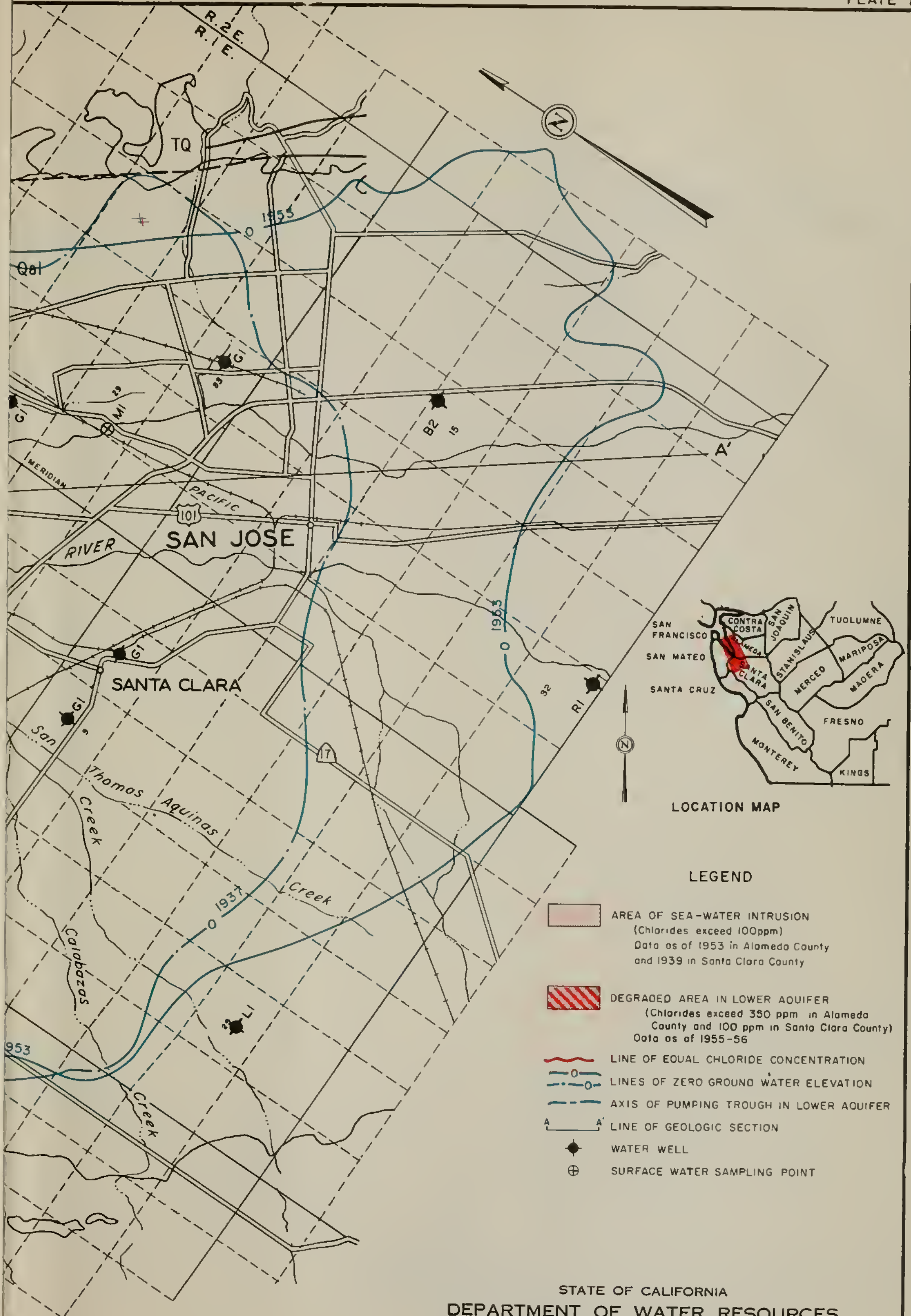

Note: No Fall Measurements
For 1954-56
Note: No Fall Measurements
For 1953-56
1956
1957


Note: No Fall Measurements
For 1954-56
Note: No Fall Measurements
For 1953-56
1956
1957



WATER LEVEL FLUCTUATIONS IN WELLS

PETALUMA AND NAPA-SONOMA VALLEYS



STATE OF CALIFORNIA
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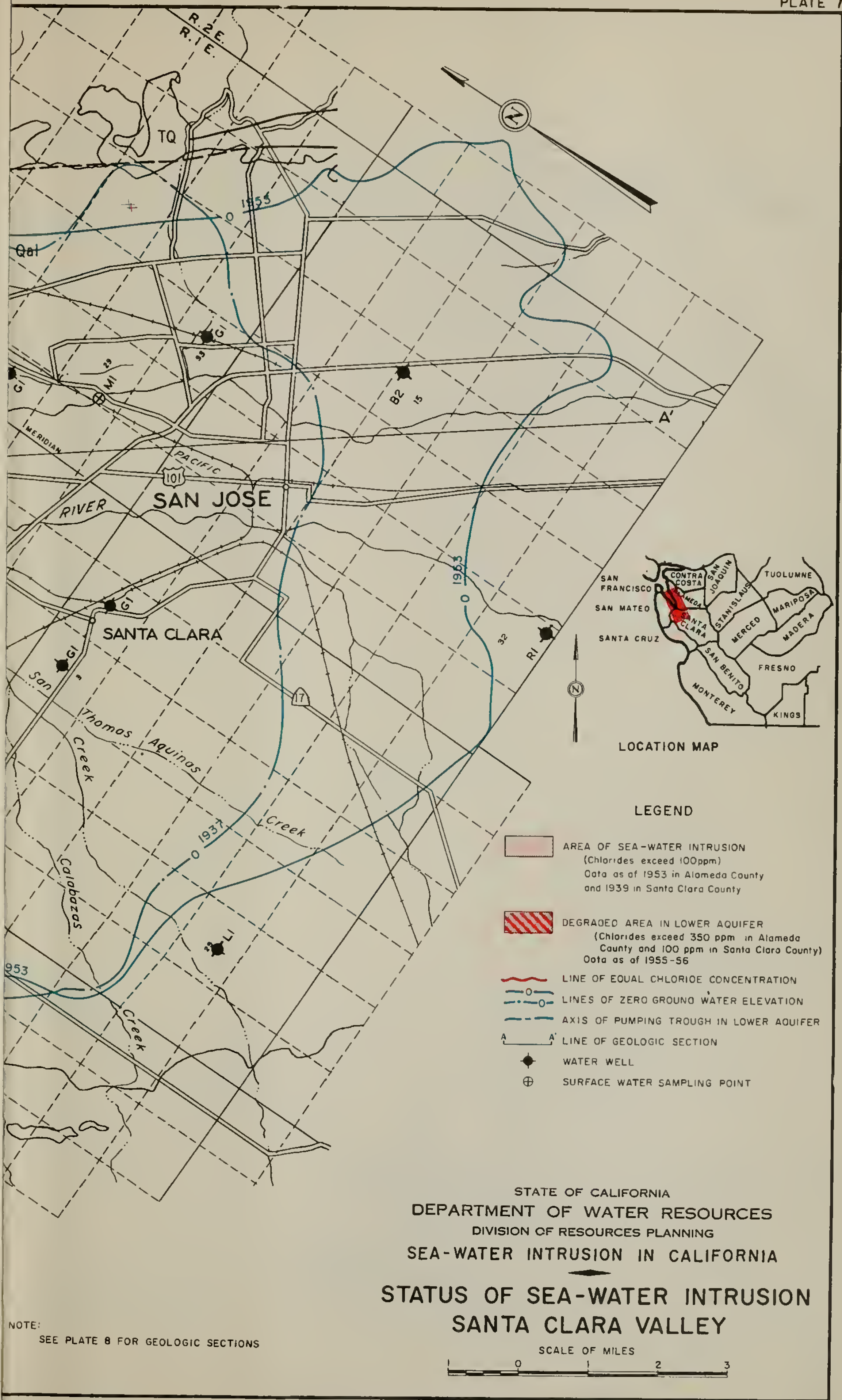
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

STATUS OF SEA-WATER INTRUSION SANTA CLARA VALLEY

SCALE OF MILES

1 0 1 2 3

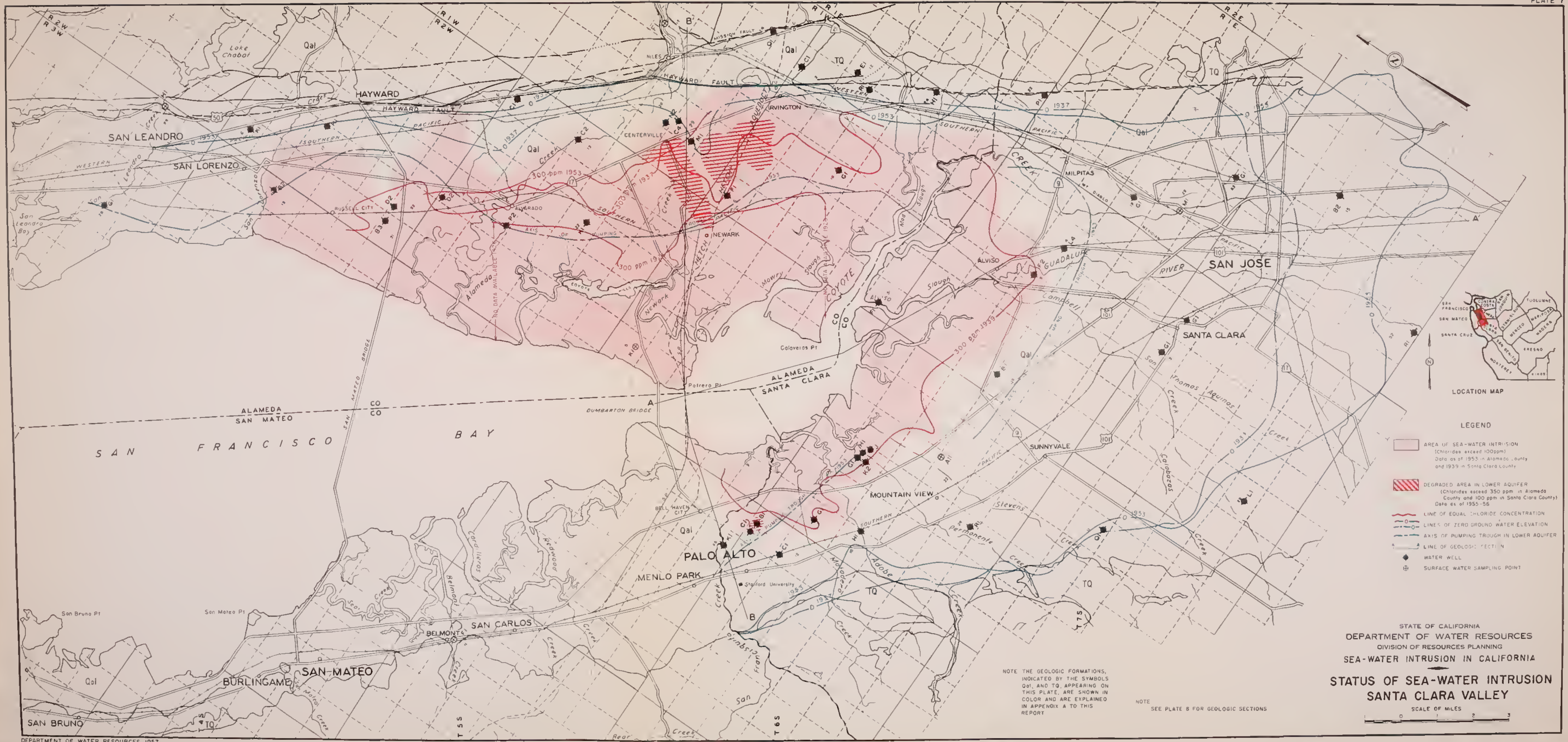
NOTE:
SEE PLATE 8 FOR GEOLOGIC SECTIONS



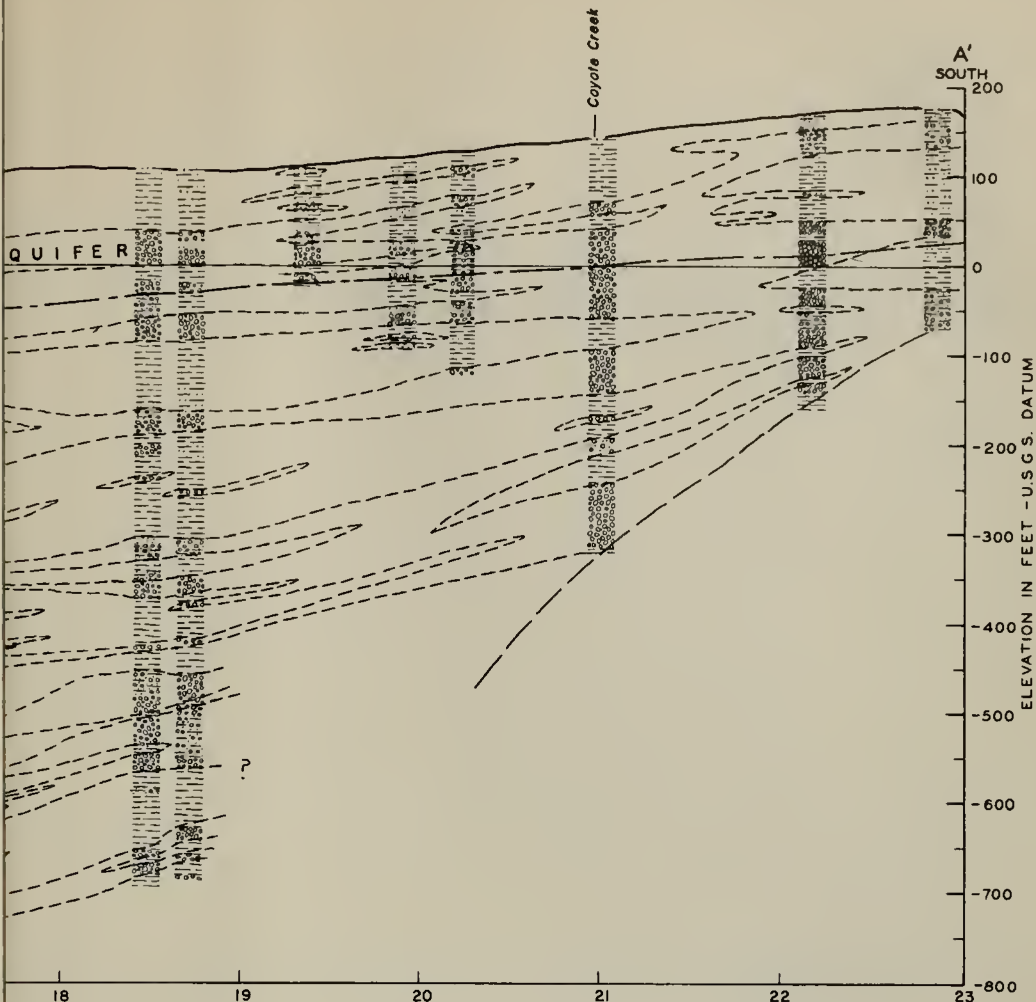
NOTE:
SEE PLATE 8 FOR GEOLOGIC SECTIONS

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

STATUS OF SEA-WATER INTRUSION
SANTA CLARA VALLEY



DEPARTMENT OF WATER RESOURCES 1957



LEGEND

SLIGHTLY PERMEABLE TO IMPERMEABLE MATERIALS
- CLAY
- SANDY CLAY
- CLAY, SAND AND GRAVEL

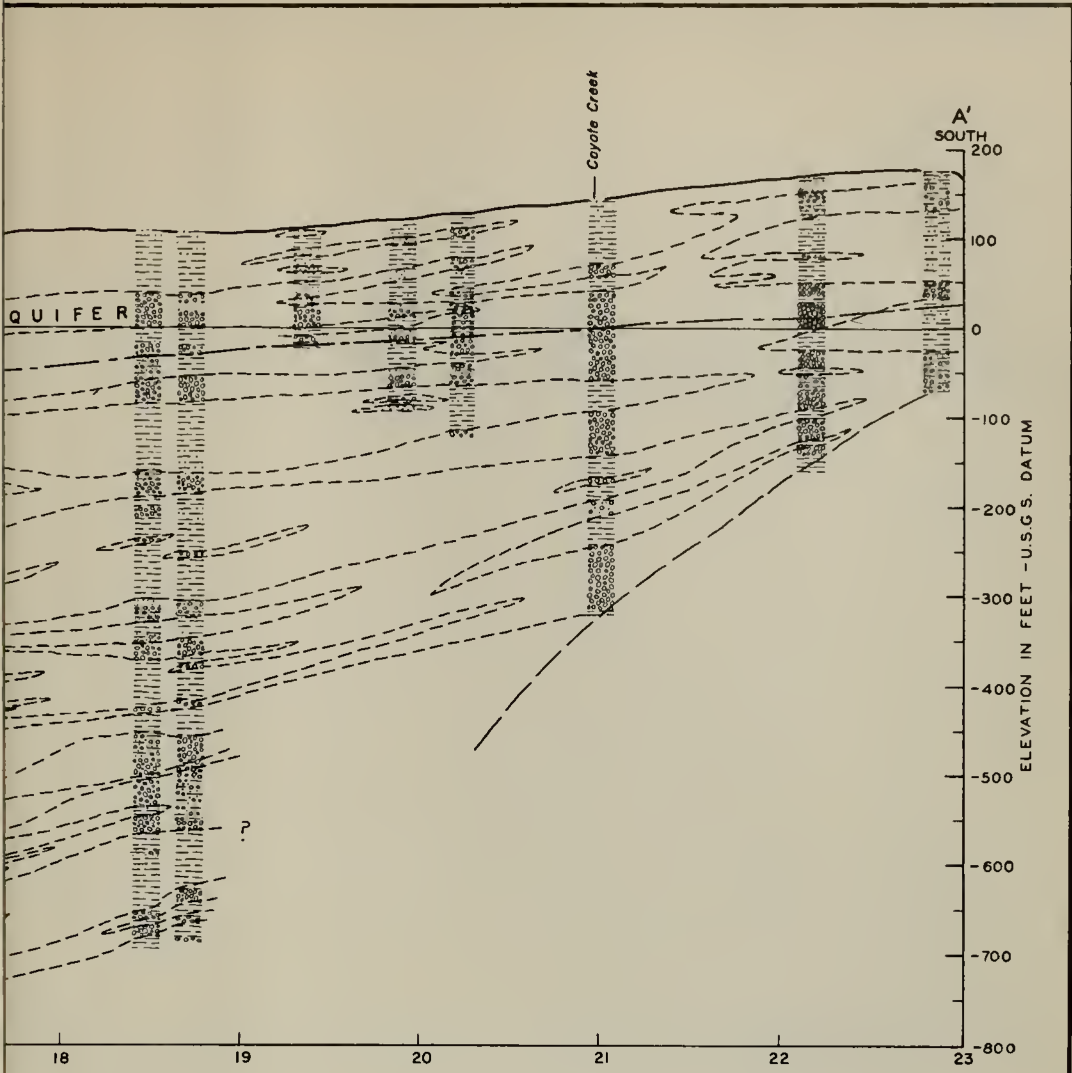
MODERATELY PERMEABLE TO PERMEABLE MATERIALS
- SAND
- SANDY GRAVEL
- GRAVEL

PORTION OF PERMEABLE DEPOSITS CONTAINING GROUND WATER WITH CHLORIDE CONCENTRATION GREATER THAN 100 PARTS PER MILLION

NOTE:
LINES OF GEOLOGIC SECTIONS SHOWN ON PLATE 7

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

GEOLOGIC SECTIONS A-A' AND B-B'
SANTA CLARA VALLEY



LEGEND

SLIGHTLY PERMEABLE TO IMPERMEABLE MATERIALS
- CLAY
- SANDY CLAY
- CLAY, SAND AND GRAVEL

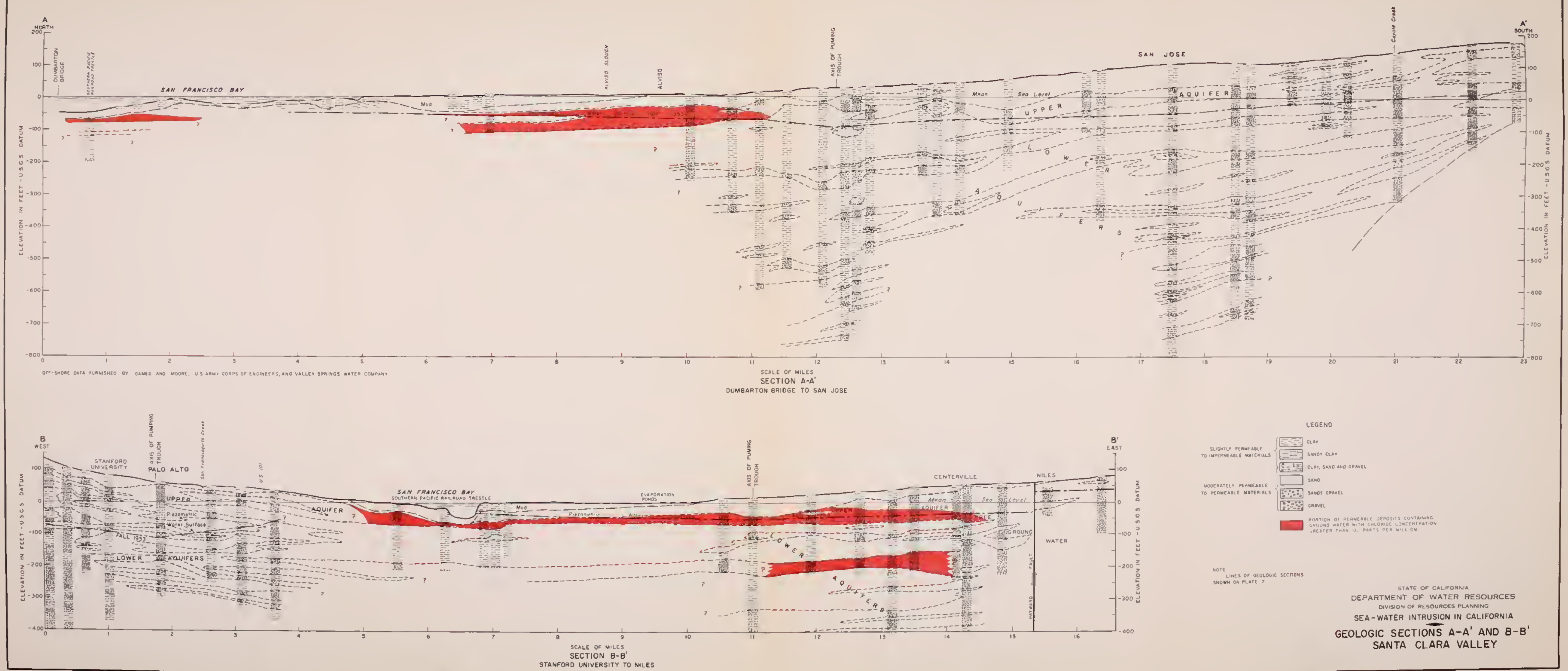
MODERATELY PERMEABLE TO PERMEABLE MATERIALS
- SAND
- SANDY GRAVEL
- GRAVEL

PORTION OF PERMEABLE DEPOSITS CONTAINING GROUND WATER WITH CHLORIDE CONCENTRATION GREATER THAN 100 PARTS PER MILLION

NOTE:
LINES OF GEOLOGIC SECTIONS SHOWN ON PLATE 7

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

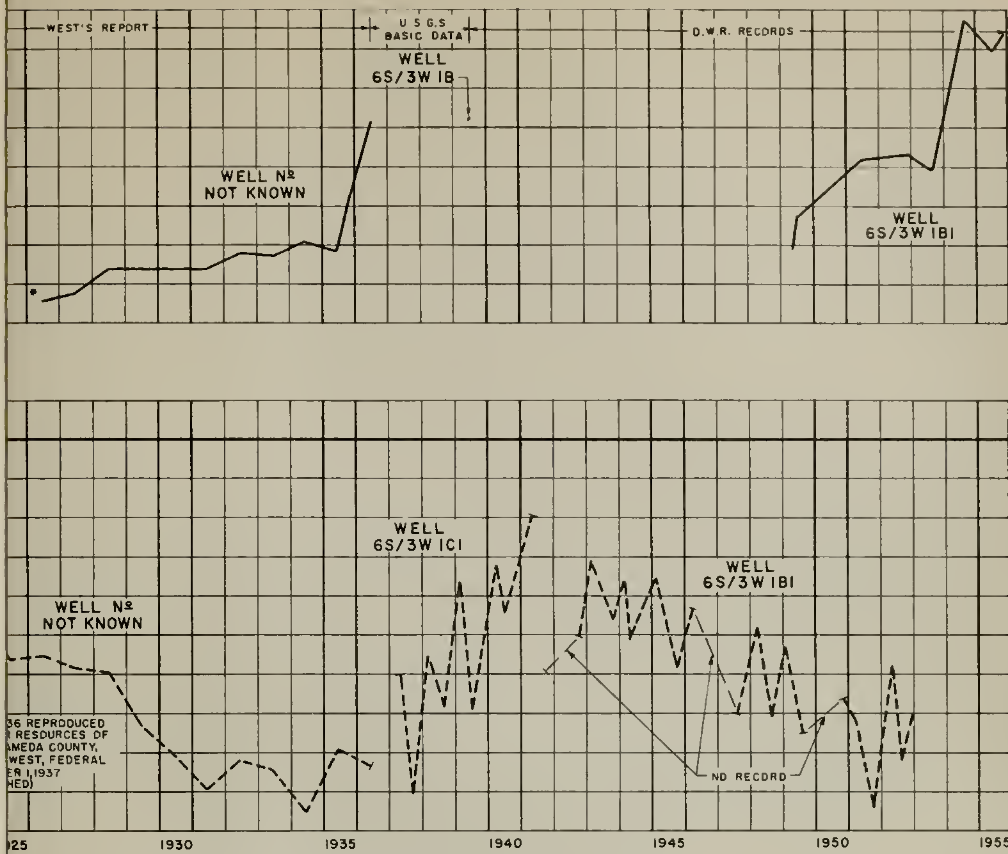
GEOLOGIC SECTIONS A-A' AND B-B'
SANTA CLARA VALLEY



STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

GEOLOGIC SECTIONS A-A' AND B-B'
SANTA CLARA VALLEY

DEPARTMENT OF WATER RESOURCES 1957

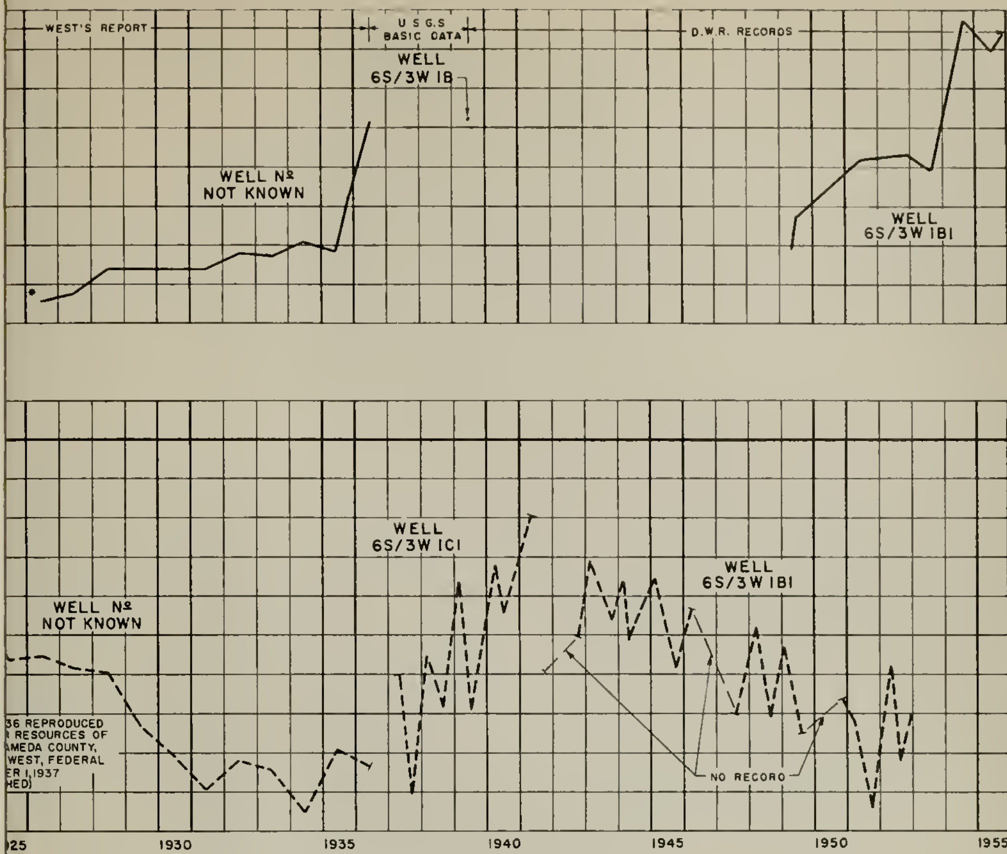


SOUTH BAY PALO ALTO AREA
[LOWER AQUIFER]

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

CHANGES IN CHLORIDE CONCENTRATION AND WATER LEVEL FLUCTUATIONS IN WELLS SANTA CLARA VALLEY



SOUTH BAY PALO ALTO AREA
[LOWER AQUIFER]

STATE OF CALIFORNIA
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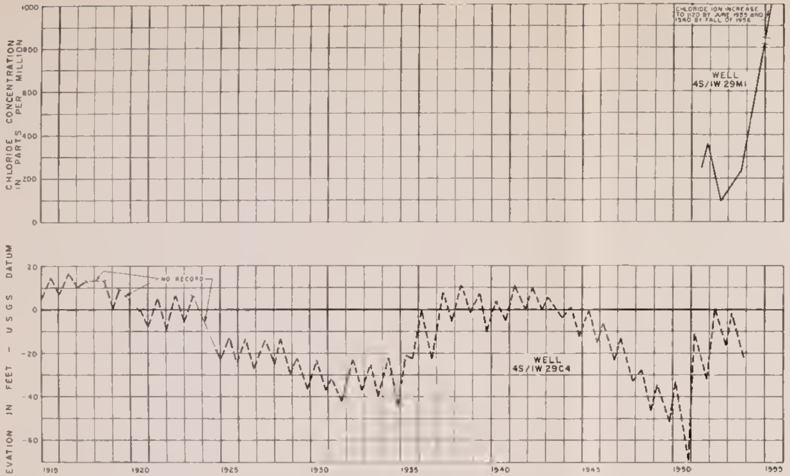
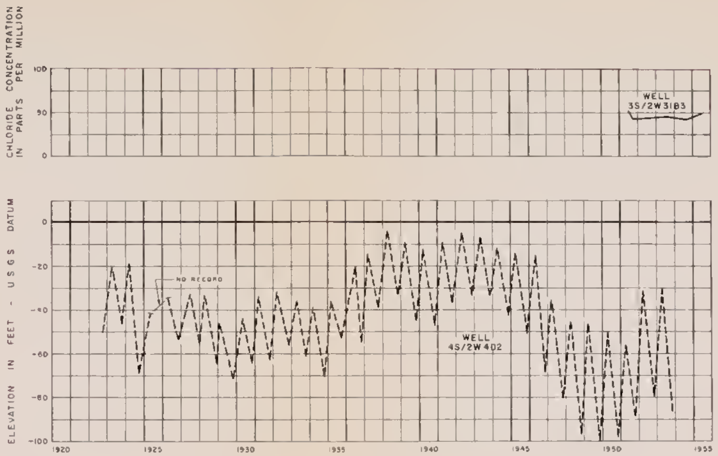
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

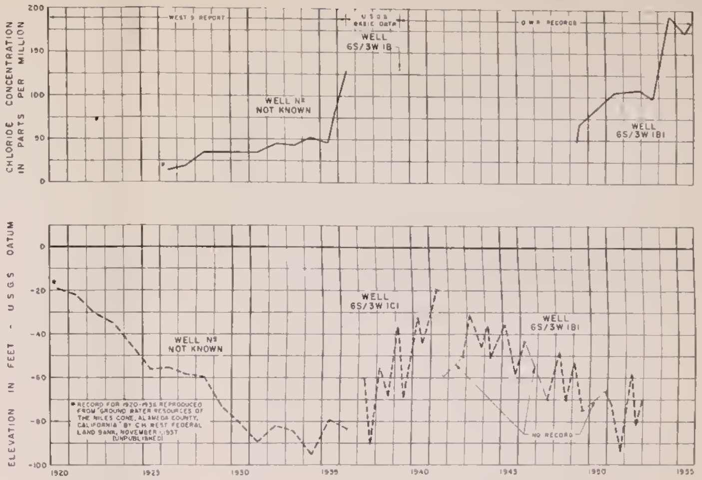
CHANGES IN CHLORIDE CONCENTRATION AND WATER LEVEL FLUCTUATIONS IN WELLS SANTA CLARA VALLEY



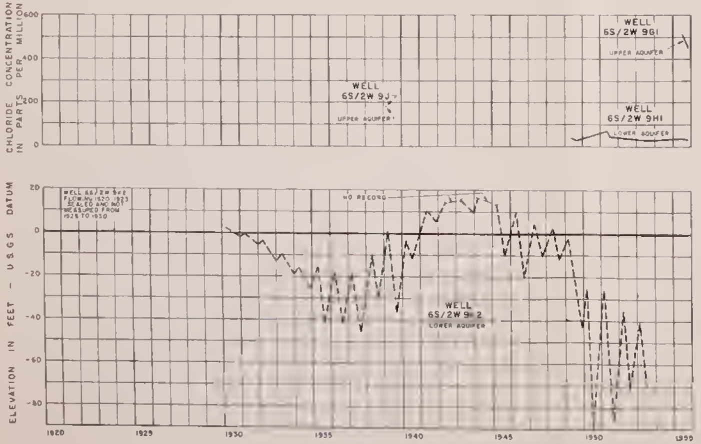
EAST BAY CENTERVILLE AREA
[UPPER AQUIFER]



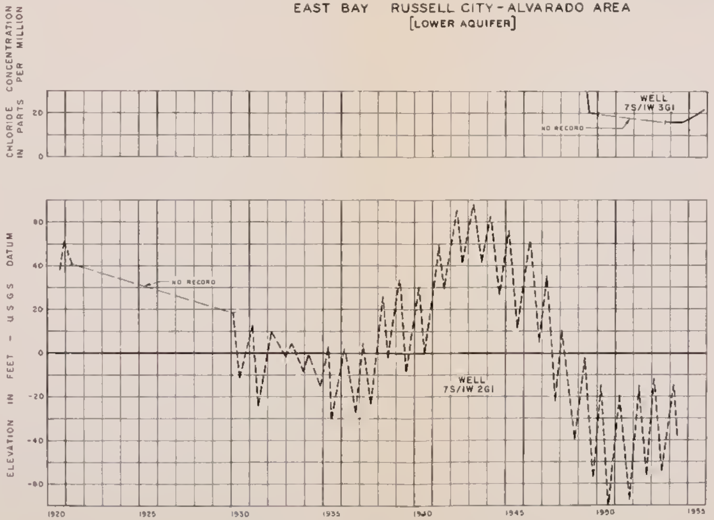
EAST BAY RUSSELL CITY-ALVARADO AREA
[LOWER AQUIFER]



SOUTH BAY PALO ALTO AREA
[LOWER AQUIFER]



SOUTH BAY



SOUTH BAY SANTA CLARA AREA
[LOWER AQUIFER]

STATE OF CALIFORNIA
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DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

CHANGES IN CHLORIDE CONCENTRATION
AND
WATER LEVEL FLUCTUATIONS IN WELLS
SANTA CLARA VALLEY

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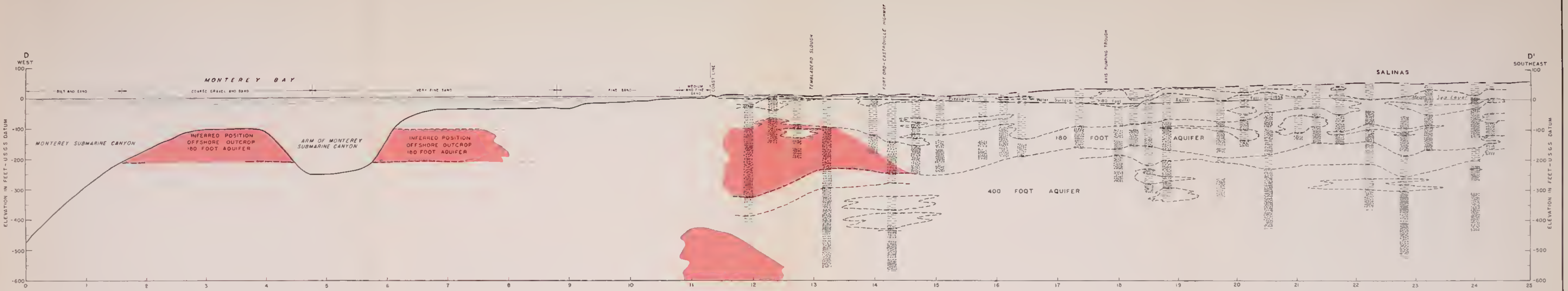
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

STATUS OF SEA-WATER INTRUSION PAJARO VALLEY AND SALINAS VALLEY PRESSURE AREA

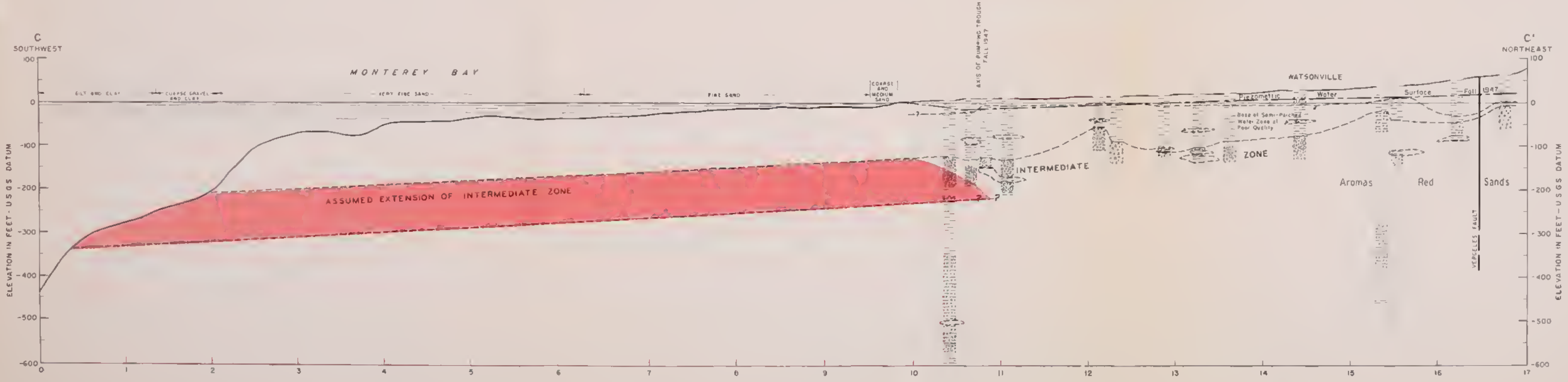
SCALE OF MILES
0 1 2 3

DEPARTMENT OF WATER RESOURCES 1957



SECTION D-D'
MONTEREY BAY TO SALINAS

NOTE: LINES OF GEOLOGIC SECTIONS SHOWN ON PLATE 10



SUBMARINE DEPOSITS FROM LITHOGRAPHIC MAP OF MONTEREY BAY, CALIFORNIA BY E. W. GALLIHER 1932

SECTION C-C'
PAJARO VALLEY

LEGEND

SLIGHTLY PERMEABLE TO IMPERMEABLE MATERIALS
- CLAY
- SANDY CLAY
- CLAY, SAND AND GRAVEL

MODERATELY PERMEABLE TO PERMEABLE MATERIALS
- SAND
- SANDY GRAVEL
- GRAVEL

PORTION OF PERMEABLE DEPOSITS CONTAINING GROUND WATER WITH CHLORIDE CONCENTRATION GREATER THAN 100 PARTS PER MILLION

STATE OF CALIFORNIA
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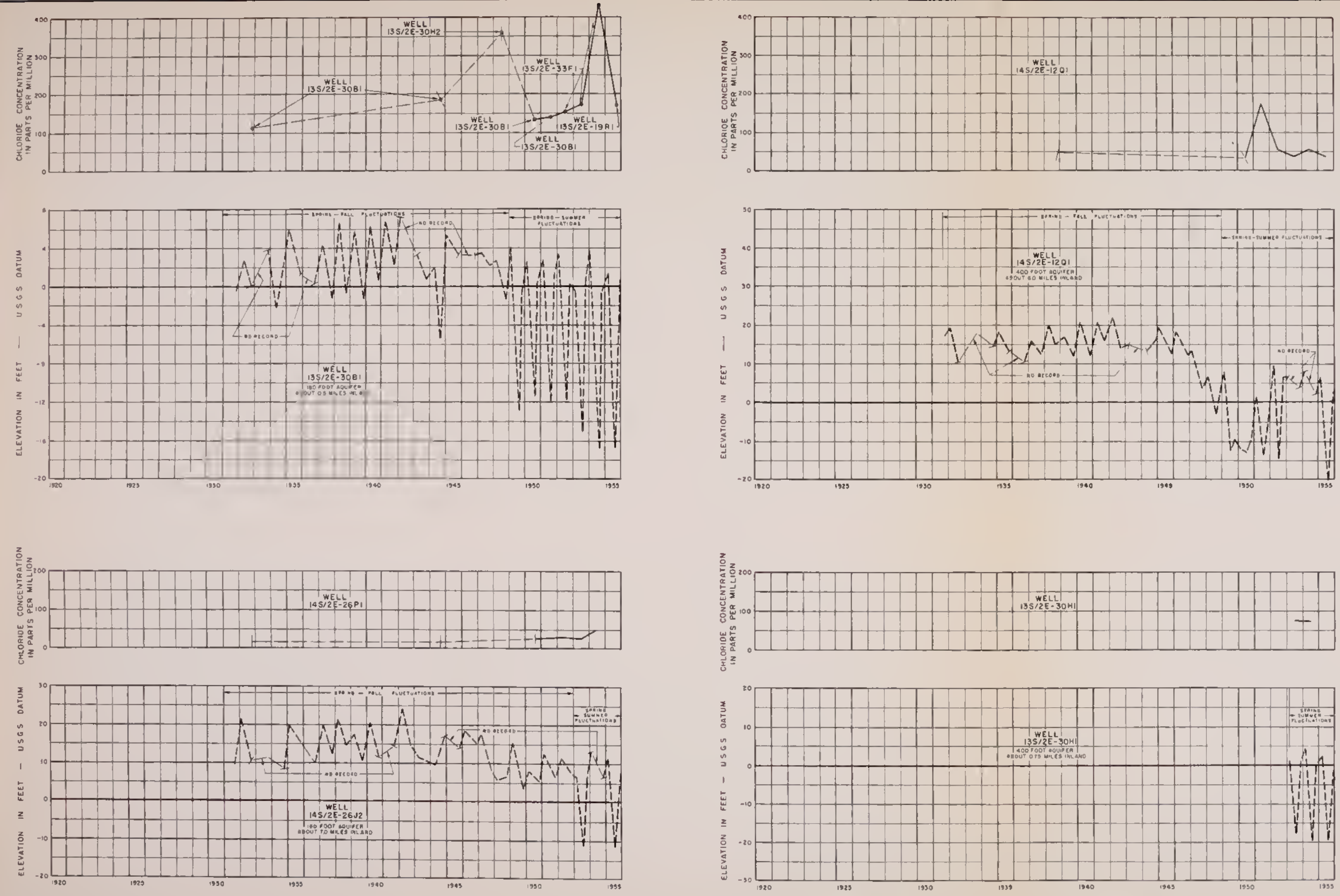
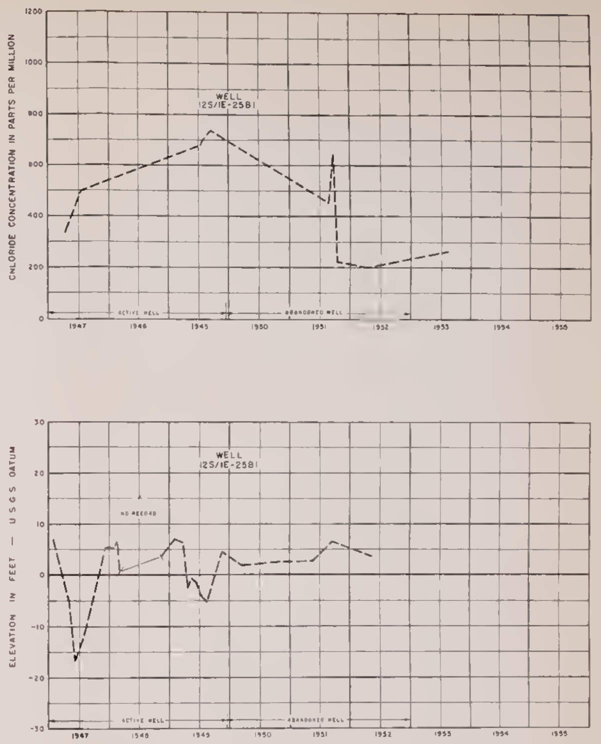
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

GEOLOGIC SECTIONS C-C' AND D-D'
PAJARO VALLEY AND SALINAS VALLEY PRESSURE AREA



SALINAS VALLEY PRESSURE AREA



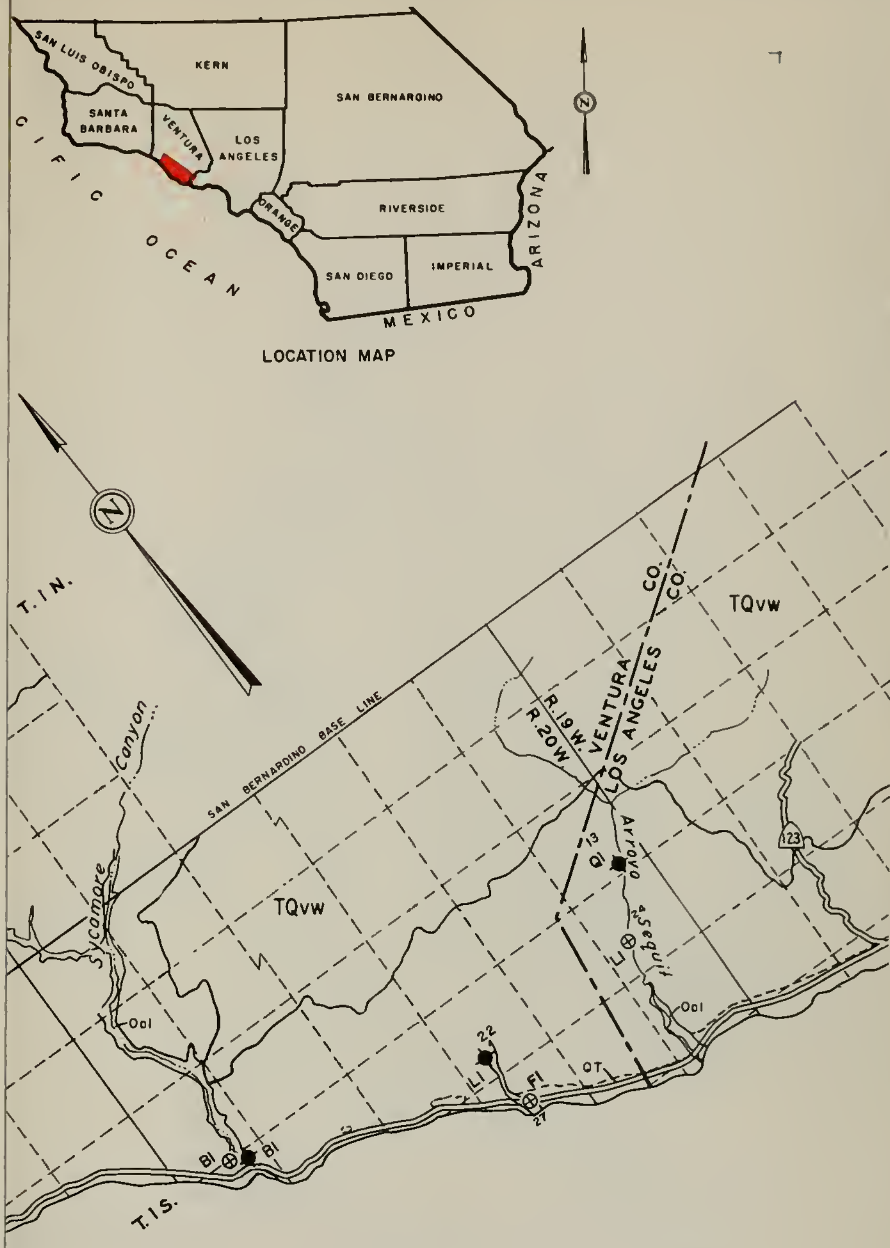
PAJARO VALLEY

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

CHANGES IN CHLORIDE CONCENTRATION AND WATER LEVEL FLUCTUATIONS IN WELLS PAJARO VALLEY AND SALINAS VALLEY PRESSURE AREA

DEPARTMENT OF WATER RESOURCES 1957



NOTE:
SEE PLATE 14 FOR GEOLOGIC SECTIONS

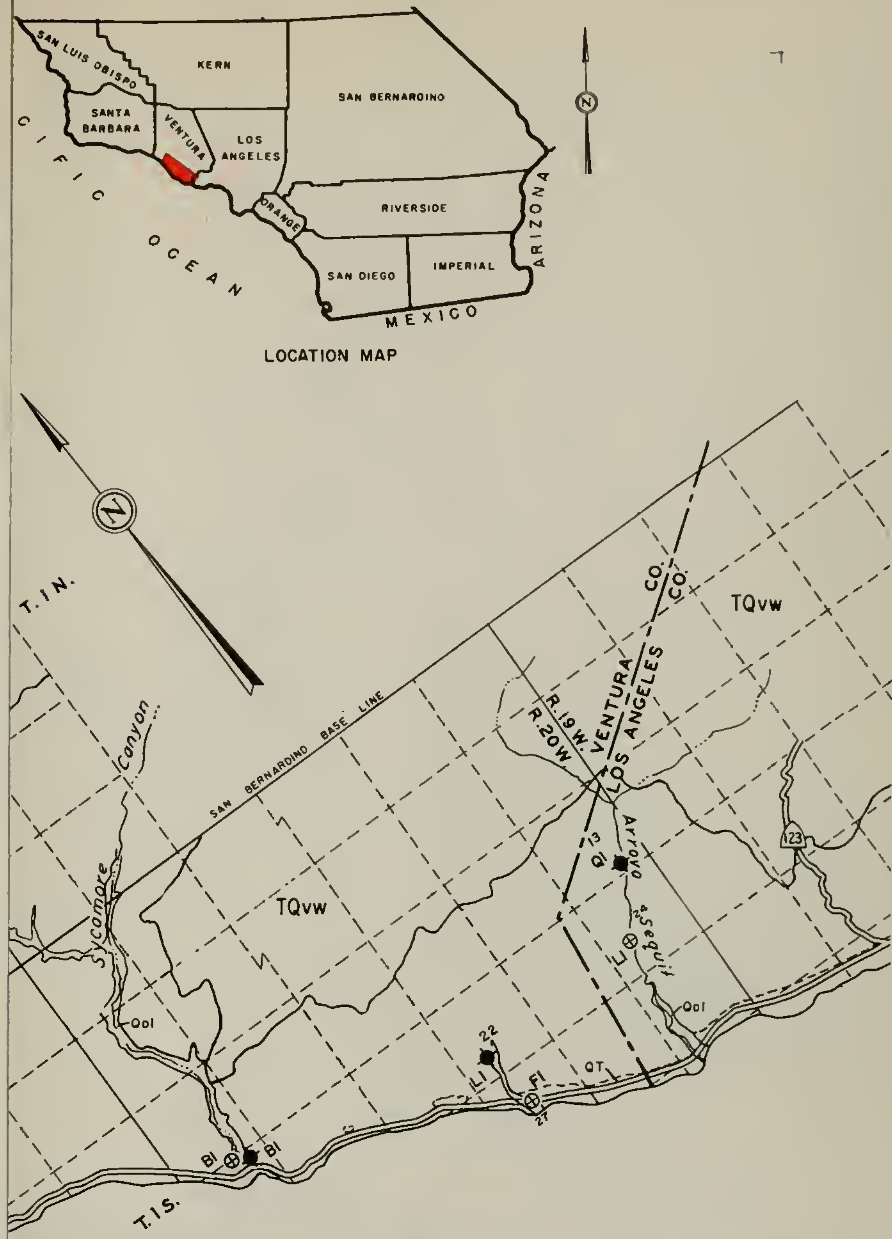
NOTE:
THE GEOLOGIC FORMATIONS INDICATED BY THE SYMBOLS Qal, TQ, Qoal, Qs, Qt AND TQvw ARE SHOWN IN COLOR AND ARE EXPLAINED IN APPENDIX A TO THIS REPORT

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

STATUS OF SEA-WATER INTRUSION OXNARD PLAIN BASIN

SCALE OF MILES
1 0 1 2 3



NOTE:
SEE PLATE 14 FOR GEOLOGIC SECTIONS

NOTE:
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STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

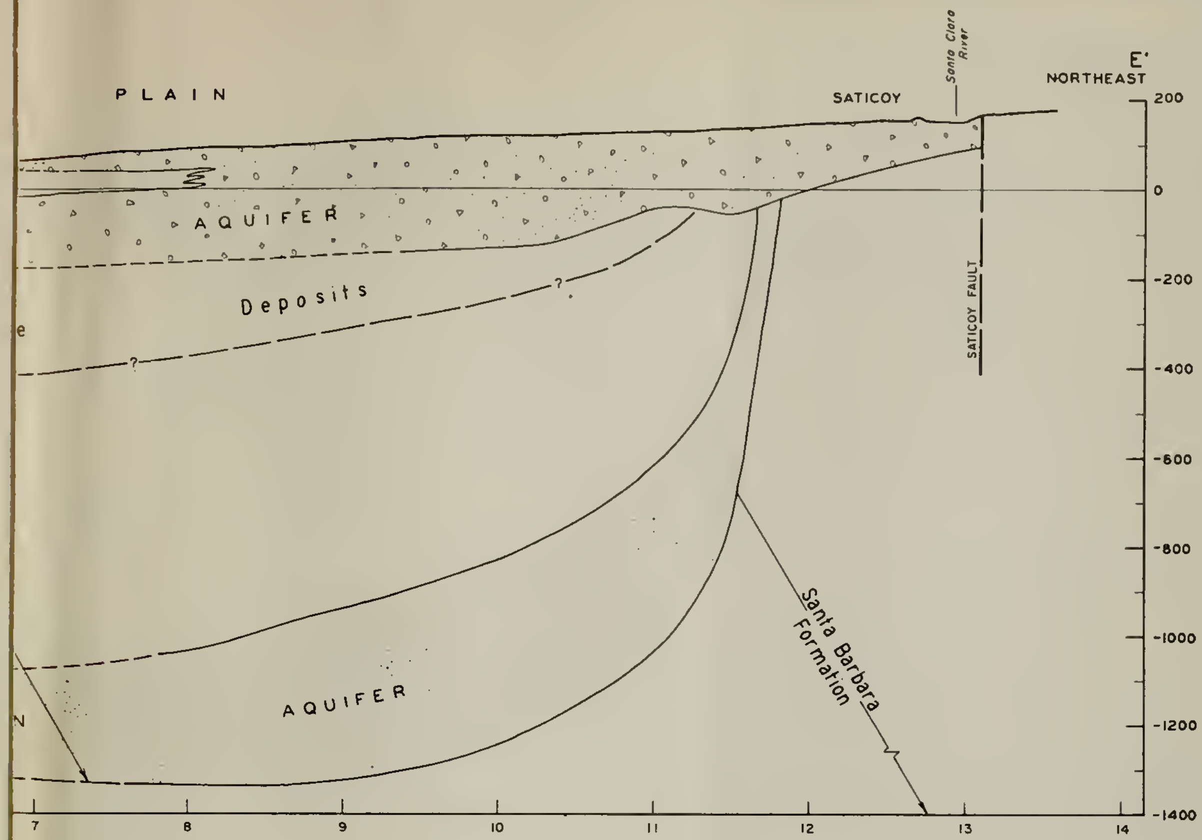
SEA-WATER INTRUSION IN CALIFORNIA

STATUS OF SEA-WATER INTRUSION OXNARD PLAIN BASIN

SCALE OF MILES

1 0 1 2 3

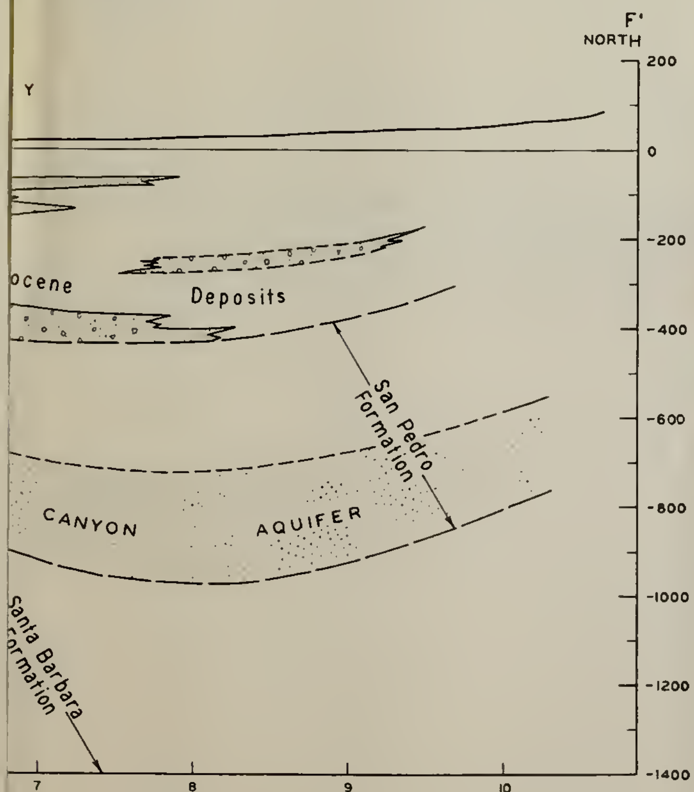

LOCATION MAP
SAN LUIS OBISPO
KERN
SAN BERNARDINO
SANTA BARBARA
VENTURA
LOS ANGELES
ORANGE
RIVERSIDE
SAN DIEGO
IMPERIAL
ARIZONA
MEXICO
PACIFIC OCEAN
VENTURA
SATICOY
EL RIO
OXNARD
CAMARILLO
PORT HUENEME
Point Mugu
Mugu Lagoon
OXNARD FOREBAY BASIN
MOUND BASIN
OXNARD PLAIN BASIN
SANTA CLARA RIVER
Revolon
Creek
Calleguas
Long Grade Canyon
Conejo Canyon
Arroyo Sequit
PUMPING TROUGH
AXIS OF PUMPING TROUGH
SOUTHERN PACIFIC
SAN BERNARDINO BASE LINE
VENTURA CO.
LOS ANGELES CO.
R.22W.
R.23W.
R.21W.
R.22W.
R.20W.
R.21W.
R.19W.
R.20W.
T.2N.
T.1N.
T.1S.
Qal
Qoal
TQ
TQvw
Qs
1955
100 ppm 1951
2000 ppm 1955
5000 ppm 1955
100 ppm 1951
E
F
PACIFIC OCEAN
NOTE.
SEE PLATE 14 FOR GEOLOGIC SECTIONS
NOTE:
THE GEOLOGIC FORMATIONS INDICATED BY THE SYMBOLS Qal, TQ, Qoal, Qs, Qt AND TQvw ARE SHOWN IN COLOR AND ARE EXPLAINED IN APPENDIX A TO THIS REPORT
LEGEND
AREA OF SEA-WATER INTRUSION (Chlorides exceed 100ppm) Data as of Dec 1955
LINE OF EQUAL CHLORIDE CONCENTRATION
LINE OF ZERO GROUND WATER ELEVATION
AXIS OF PUMPING TROUGH
LINE OF GEOLOGIC SECTION
WATER WELL
SURFACE WATER SAMPLING POINT
BASIN BOUNDARY
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA
STATUS OF SEA-WATER INTRUSION
OXNARD PLAIN BASIN
SCALE OF MILES
1 0 1 2 3



LE OF MILES

TION E-E'

NEME TO SATICOY



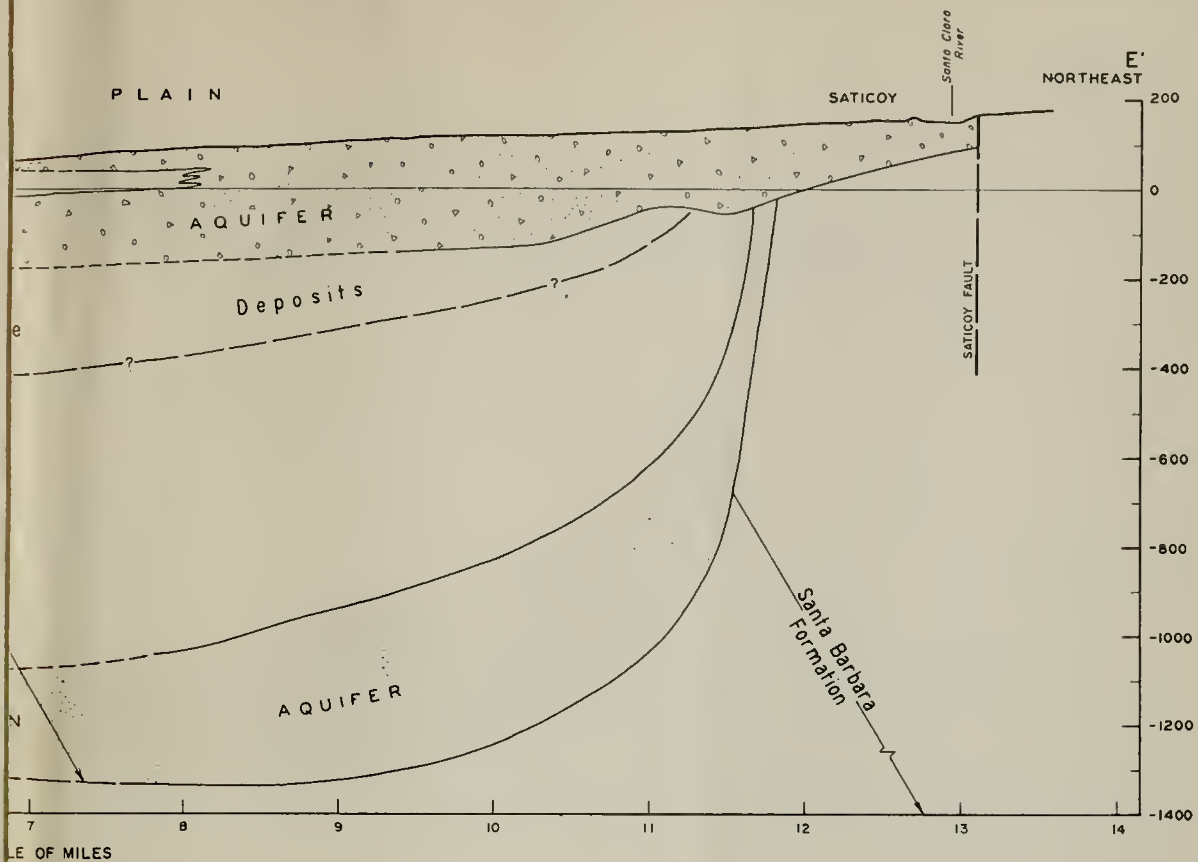
LEGEND

PORTION OF PERMEABLE DEPOSITS CONTAINING GROUND WATER WITH CHLORIDE CONCENTRATION GREATER THAN 100 PARTS PER MILLION

NOTE:
LINES OF GEOLOGIC SECTIONS SHOWN ON PLATE 13

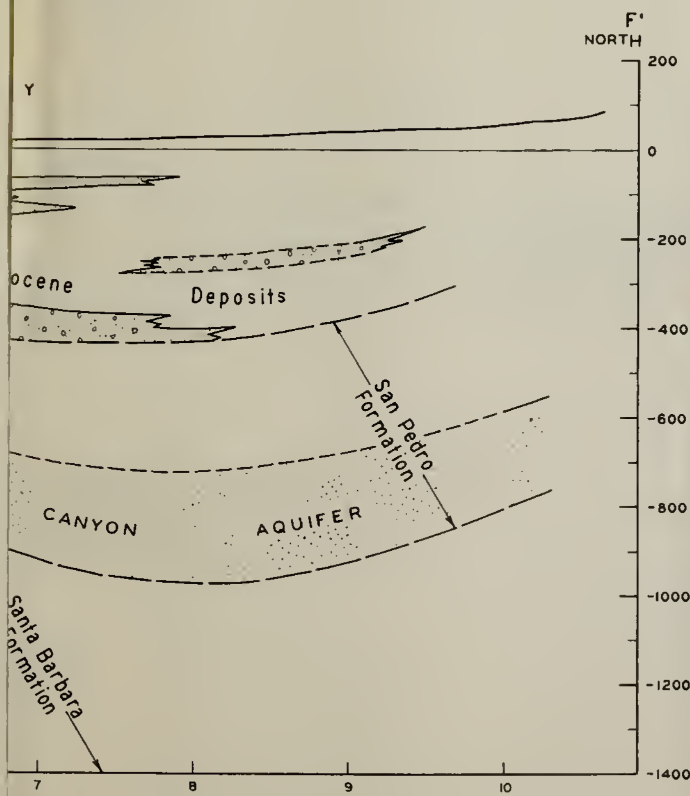
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

GEOLOGIC SECTIONS E-E', F-F'
OXNARD PLAIN BASIN



TION E-E'

NEME TO SATICOY



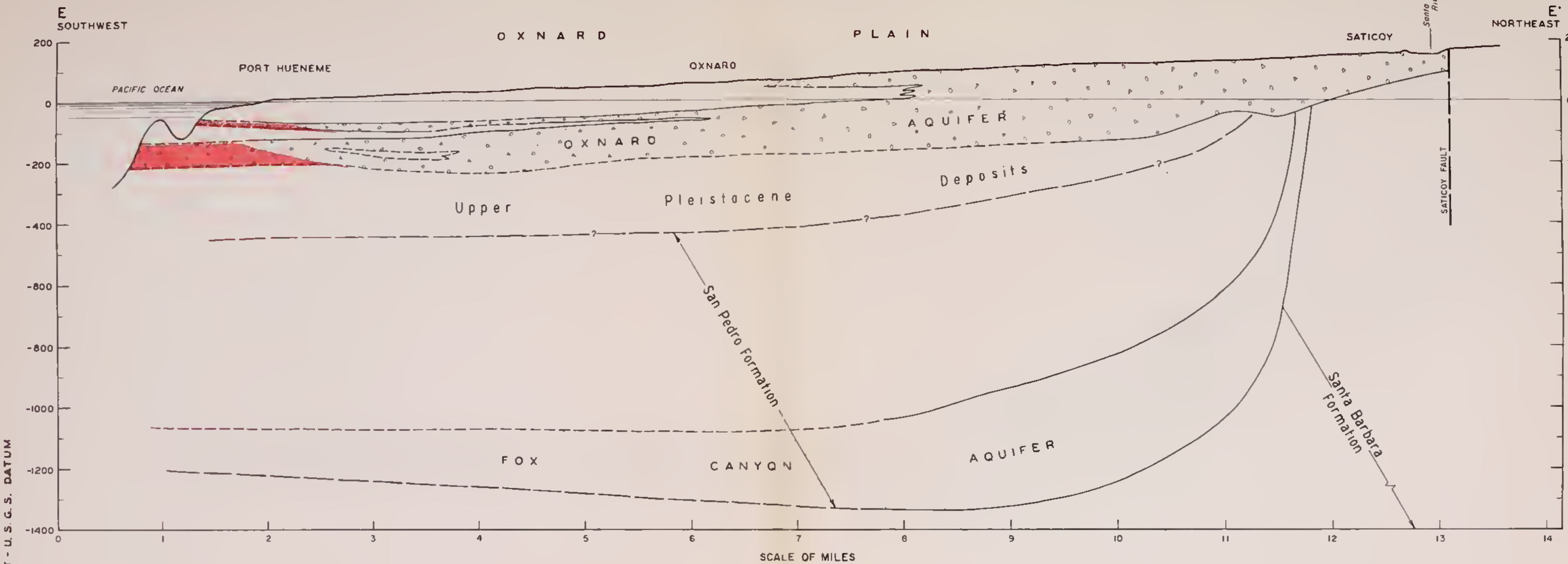
LEGEND

PORTION OF PERMEABLE DEPOSITS CONTAINING GROUND WATER WITH CHLORIDE CONCENTRATION GREATER THAN 100 PARTS PER MILLION

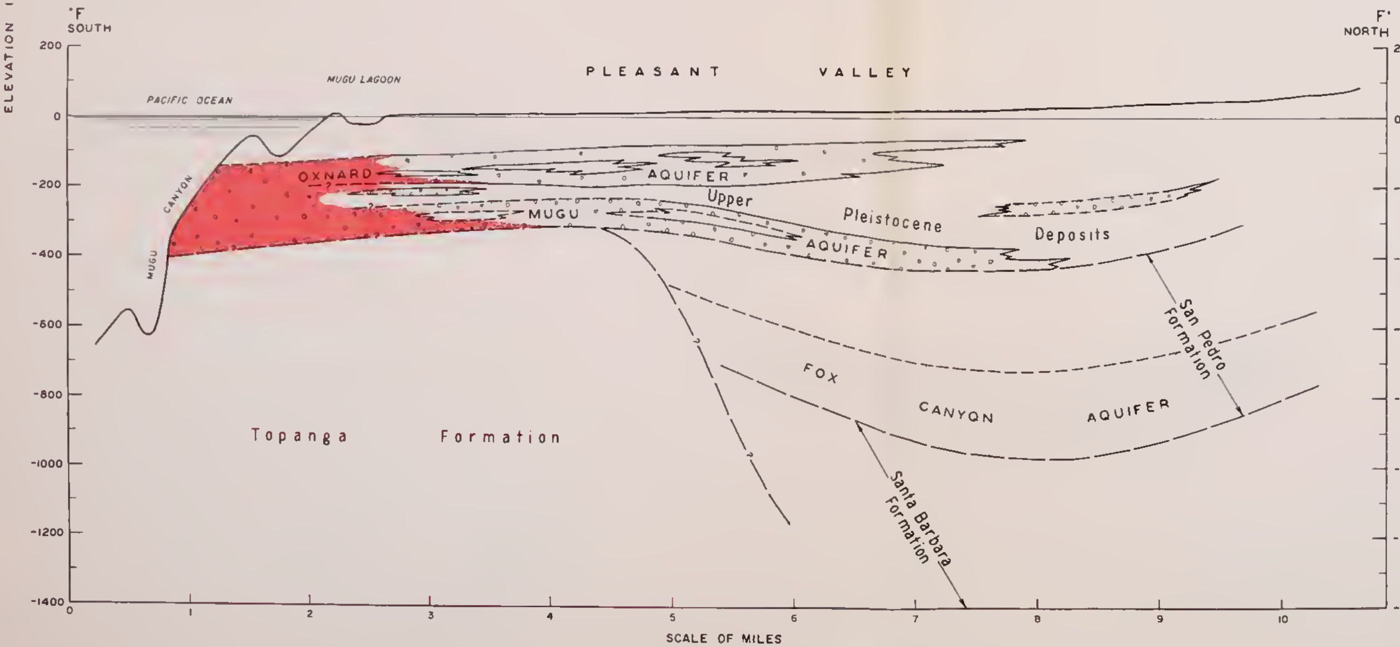
NOTE:
LINES OF GEOLOGIC SECTIONS SHOWN ON PLATE 13

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

GEOLOGIC SECTIONS E-E', F-F'
OXNARD PLAIN BASIN



SECTION E-E'
PORT HUENEME TO SATICOY



SECTION F-F'
MUGU LAGOON TO CAMARILLO AIRPORT

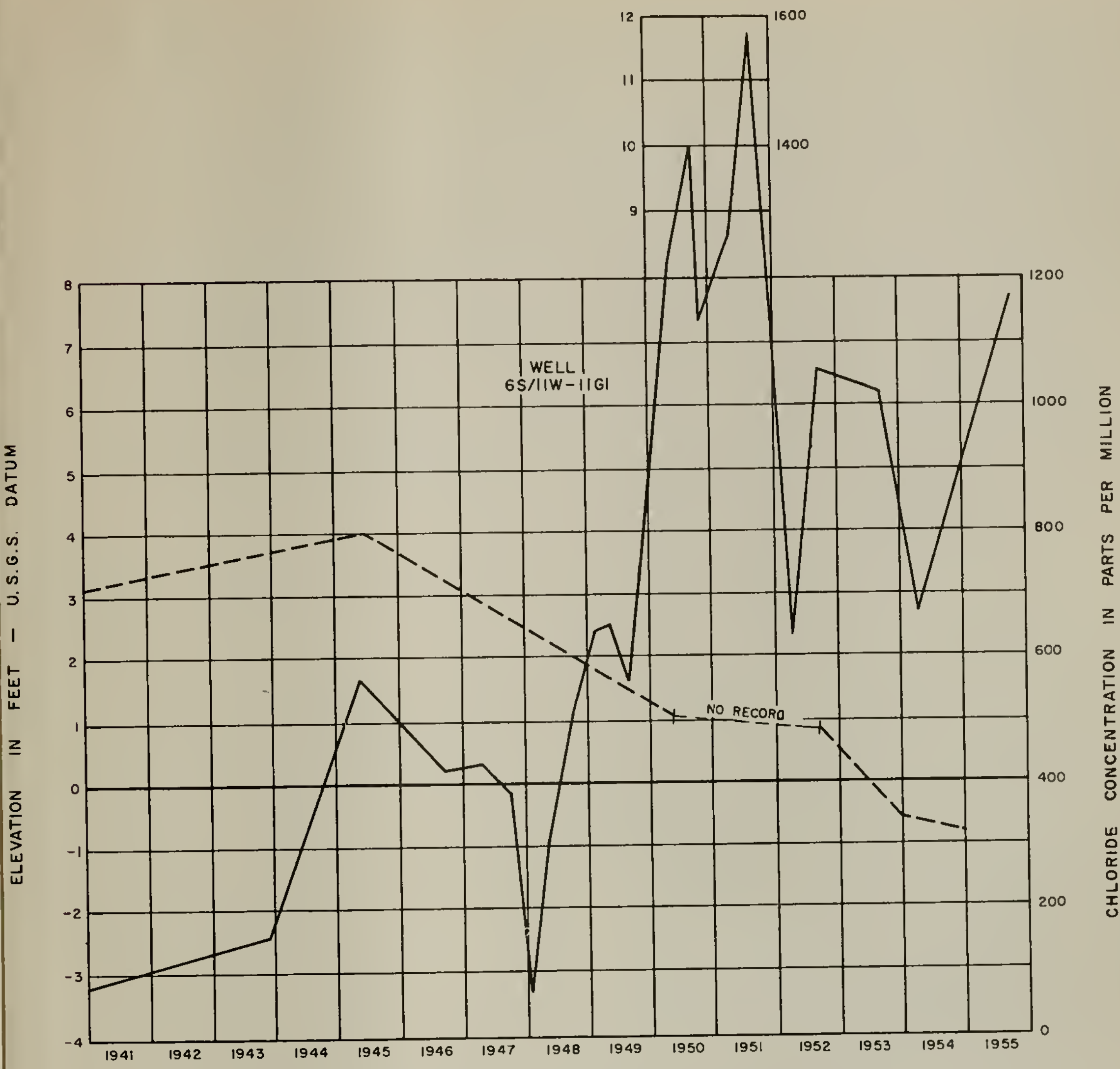
LEGEND

PORTION OF PERMEABLE DEPOSITS CONTAINING GROUND WATER WITH CHLORIDE CONCENTRATION GREATER THAN 100 PARTS PER MILLION

NOTE
LINES OF GEOLOGIC SECTIONS SHOWN ON PLATE 13

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

GEOLOGIC SECTIONS E-E', F-F'
OXNARD PLAIN BASIN



EAST COASTAL PLAIN PRESSURE AREA

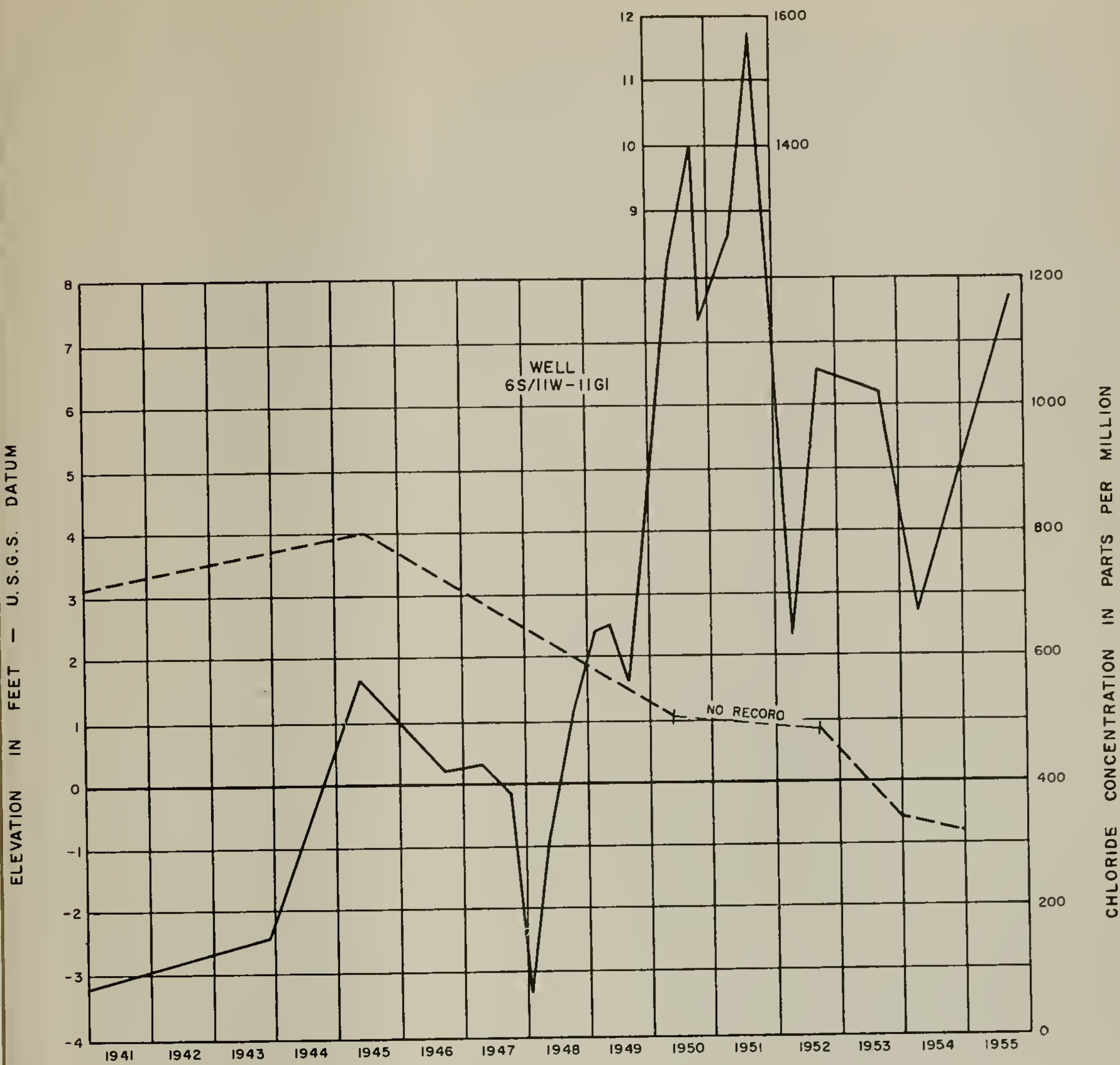
LEGEND

—— CHLORIDE CONCENTRATION

– – – WATER SURFACE ELEVATION

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

CHANGES IN CHLORIDE CONCENTRATION
AND
WATER LEVEL FLUCTUATIONS IN WELLS
OXNARD PLAIN BASIN, WEST COAST BASIN,
AND EAST COASTAL PLAIN PRESSURE AREA



EAST COASTAL PLAIN PRESSURE AREA

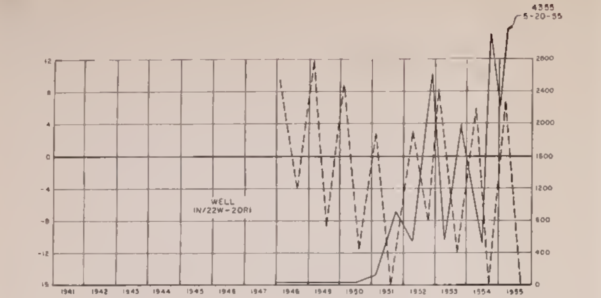
LEGEND

——— CHLORIDE CONCENTRATION

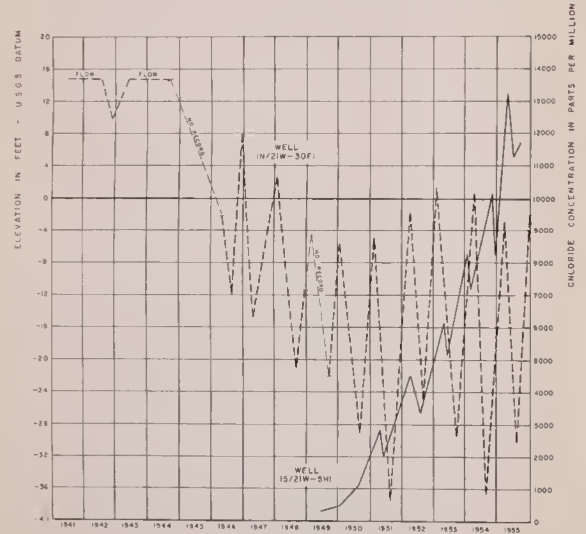
– – – WATER SURFACE ELEVATION

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

CHANGES IN CHLORIDE CONCENTRATION
AND
WATER LEVEL FLUCTUATIONS IN WELLS
OXNARD PLAIN BASIN, WEST COAST BASIN,
AND EAST COASTAL PLAIN PRESSURE AREA

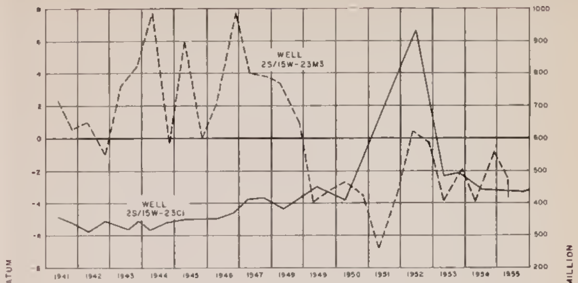


PORT HUENEME AREA

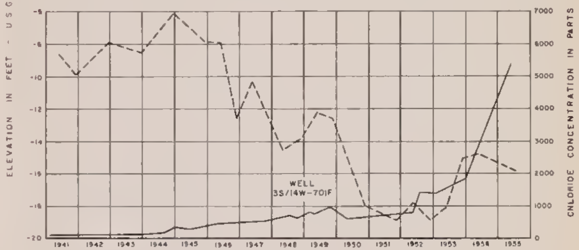


MUGU LAGUNA AREA NEAR OXNARD

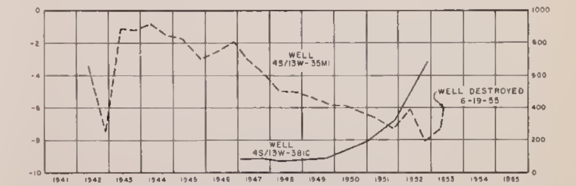
OXNARD PLAIN BASIN



PLAYA DEL REY AREA



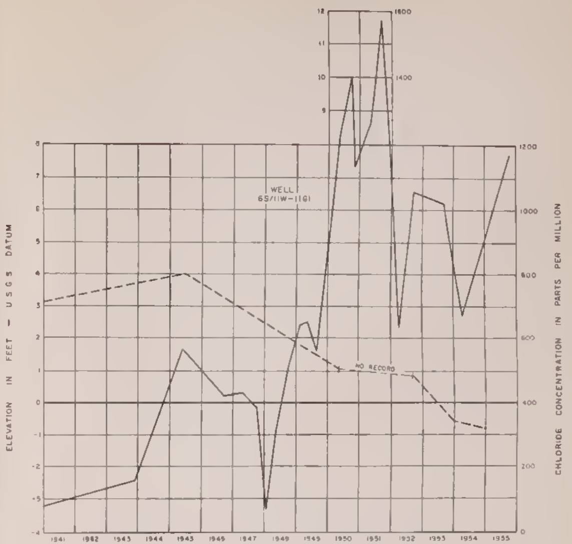
MANHATTAN BEACH AREA



LONG BEACH AREA

WEST COAST BASIN

EAST COASTAL PLAIN PRESSURE AREA



EAST COASTAL PLAIN PRESSURE AREA

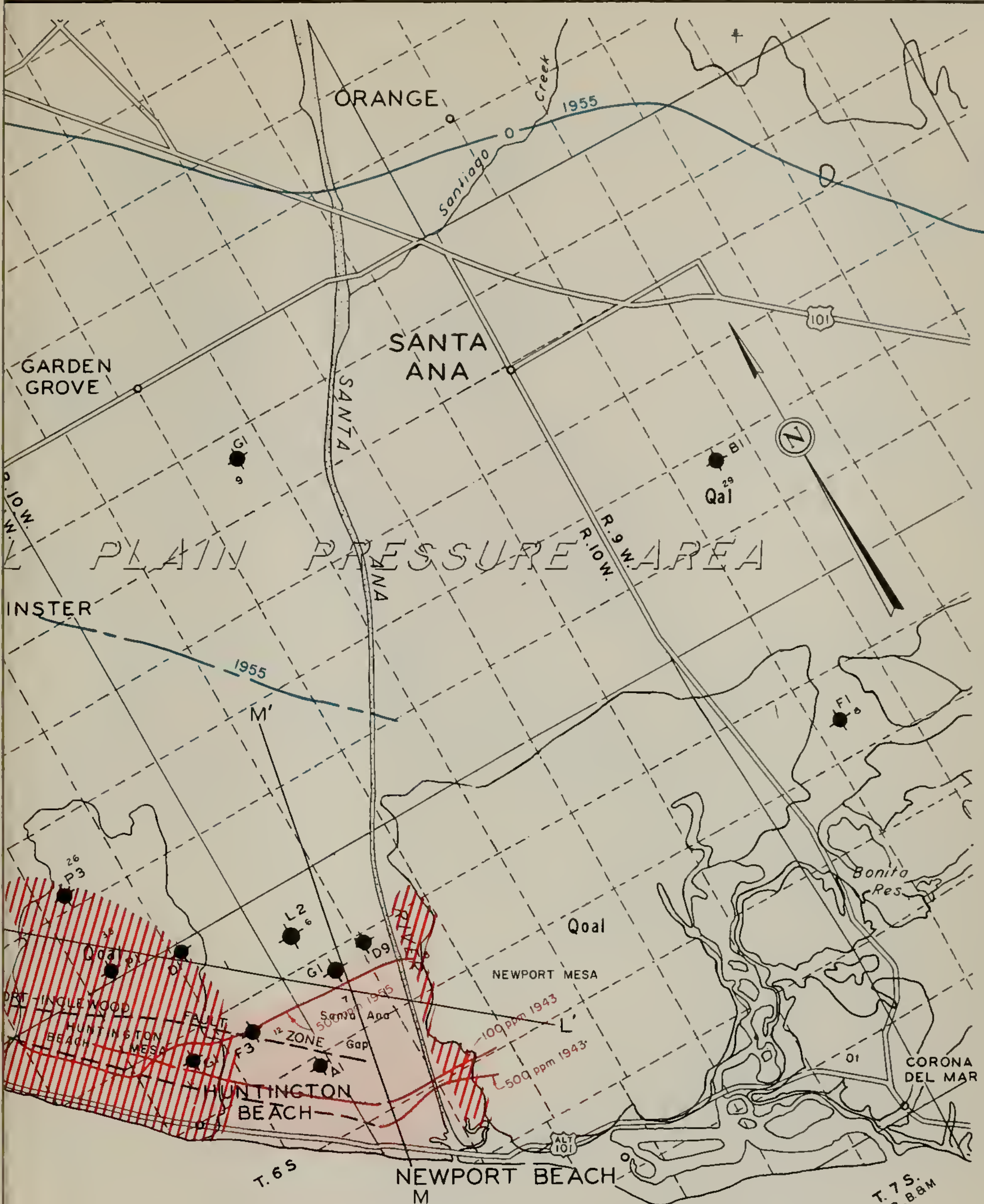
LEGEND

——— CHLORIDE CONCENTRATION

– – – WATER SURFACE ELEVATION

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

CHANGES IN CHLORIDE CONCENTRATION
AND
WATER LEVEL FLUCTUATIONS IN WELLS
OXNARD PLAIN BASIN, WEST COAST BASIN,
AND EAST COASTAL PLAIN PRESSURE AREA



IER PROJECT

RATION

VATION

R AQUIFER

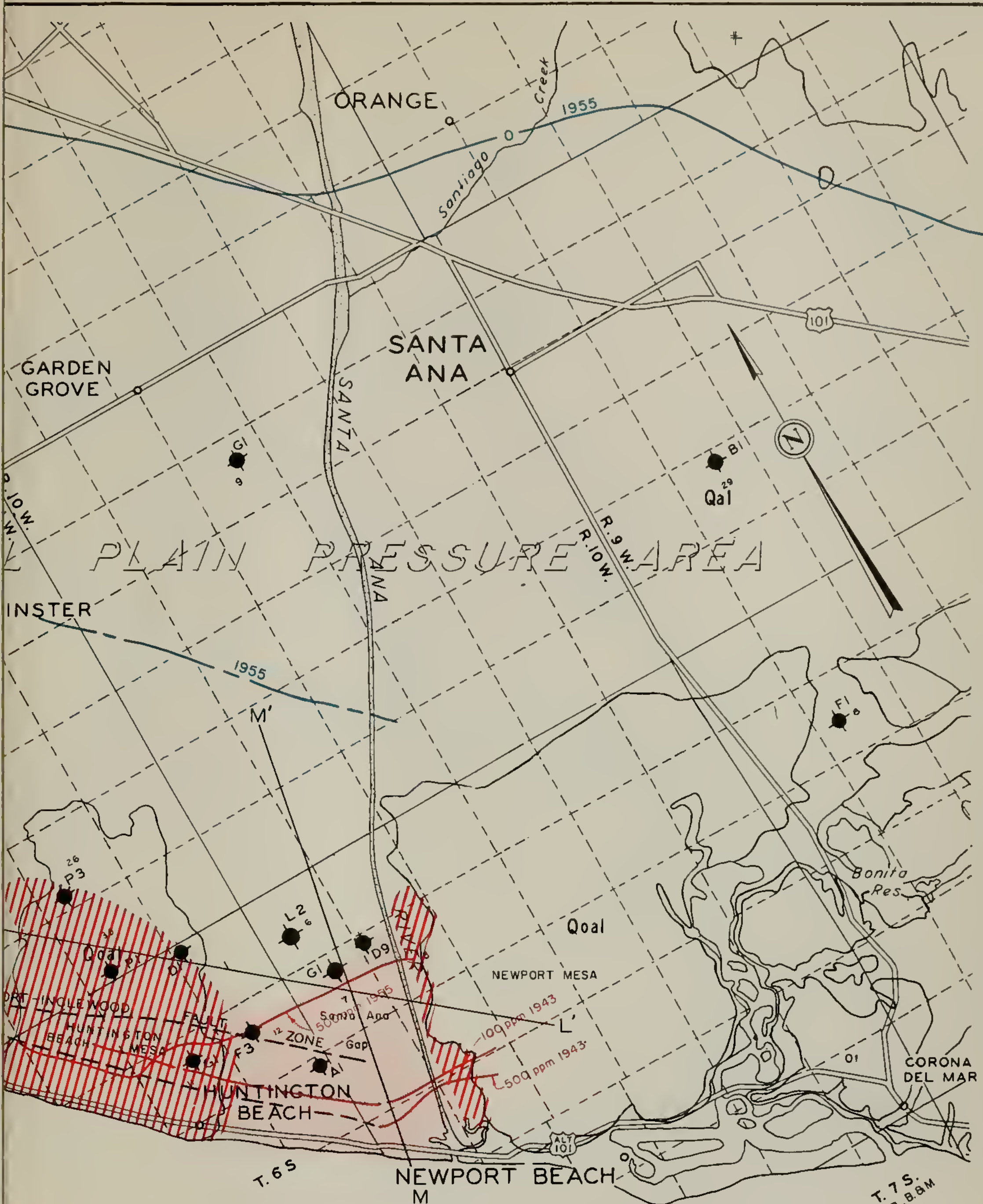
C SECTIONS

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

STATUS OF SEA-WATER INTRUSION
WEST COAST BASIN
AND
EAST COASTAL PLAIN PRESSURE AREA

SCALE OF MILES
1 0 1 2 3



IER PROJECT

RATION

VATION

R AQUIFER

C SECTIONS

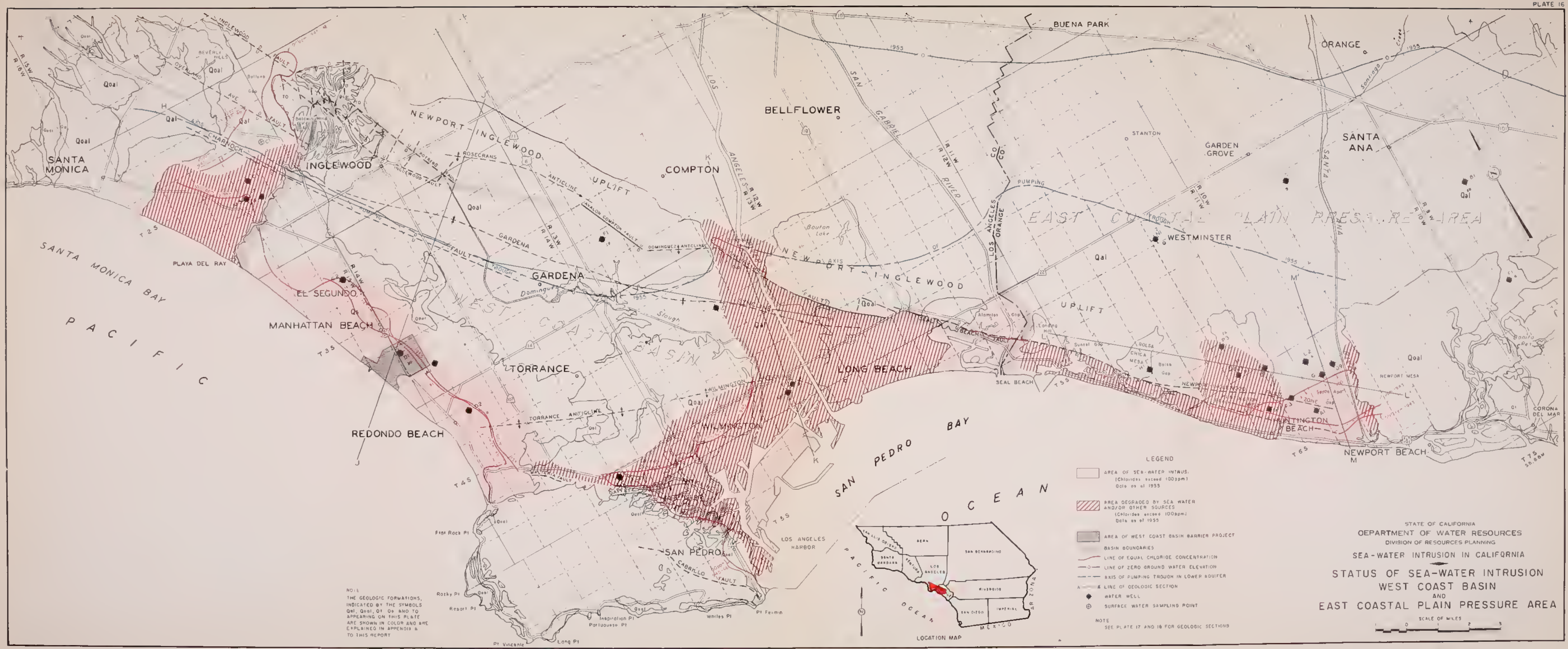
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

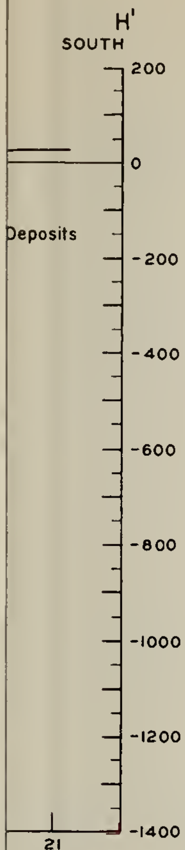
STATUS OF SEA-WATER INTRUSION WEST COAST BASIN AND EAST COASTAL PLAIN PRESSURE AREA

SCALE OF MILES

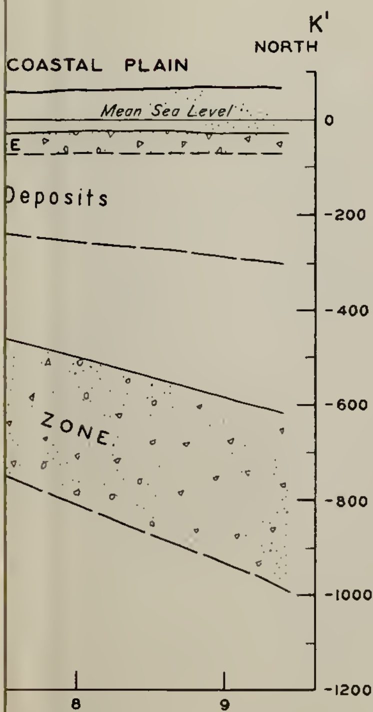
1 0 1 2 3



DEPARTMENT OF WATER RESOURCES 1957



NOTE: LINES OF GEOLOGIC SECTIONS SHOWN ON PLATE 16



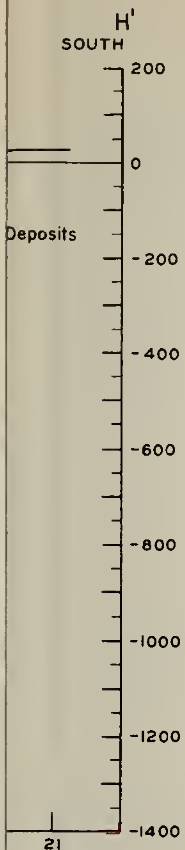
LEGEND

PORTION OF PERMEABLE DEPOSITS CONTAINING GROUND WATER WITH CHLORIDE CONCENTRATION GREATER THAN 100 PARTS PER MILLION

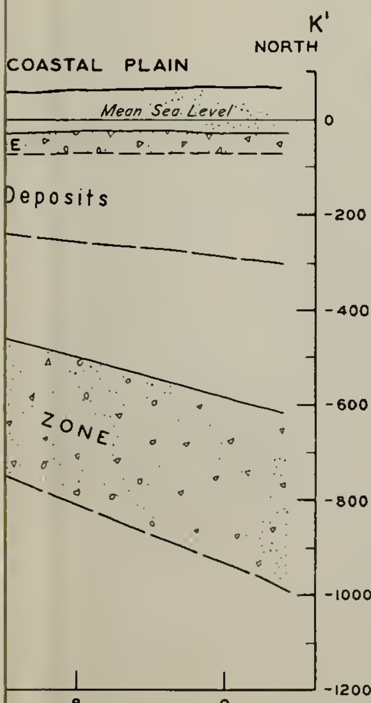
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

GEOLOGIC SECTIONS H-H', J-J', AND K-K' WEST COAST BASIN



NOTE: LINES OF GEOLOGIC SECTIONS SHOWN ON PLATE 16

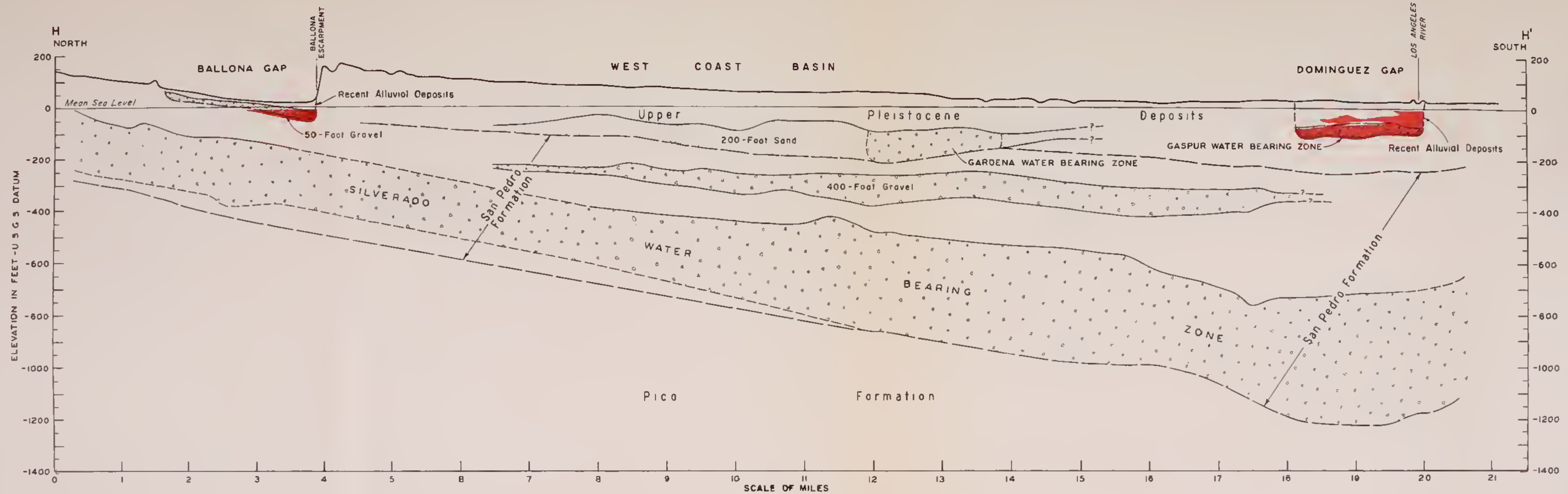


LEGEND

PORTION OF PERMEABLE DEPOSITS CONTAINING GROUND WATER WITH CHLORIDE CONCENTRATION GREATER THAN 100 PARTS PER MILLION

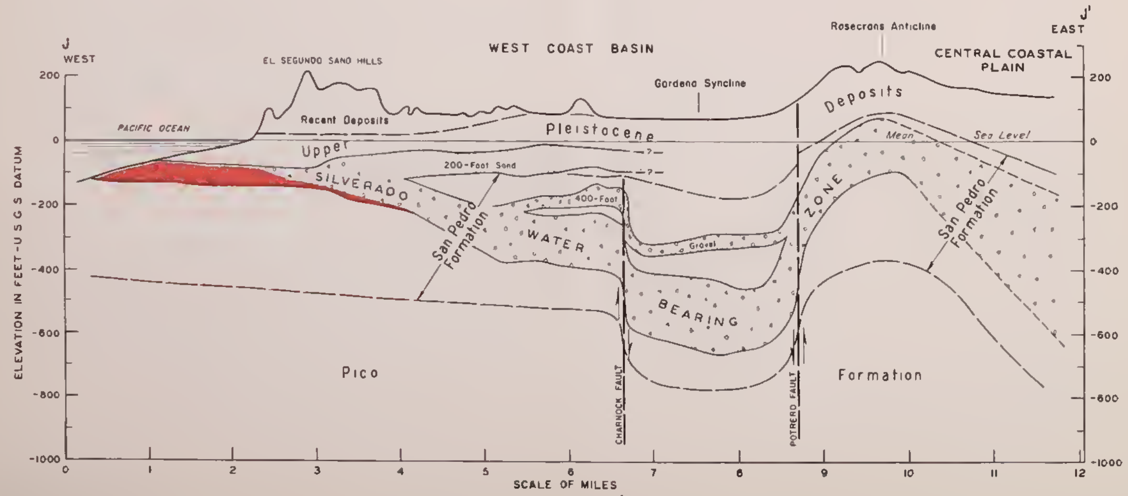
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

GEOLOGIC SECTIONS
H-H', J-J', AND K-K'
WEST COAST BASIN

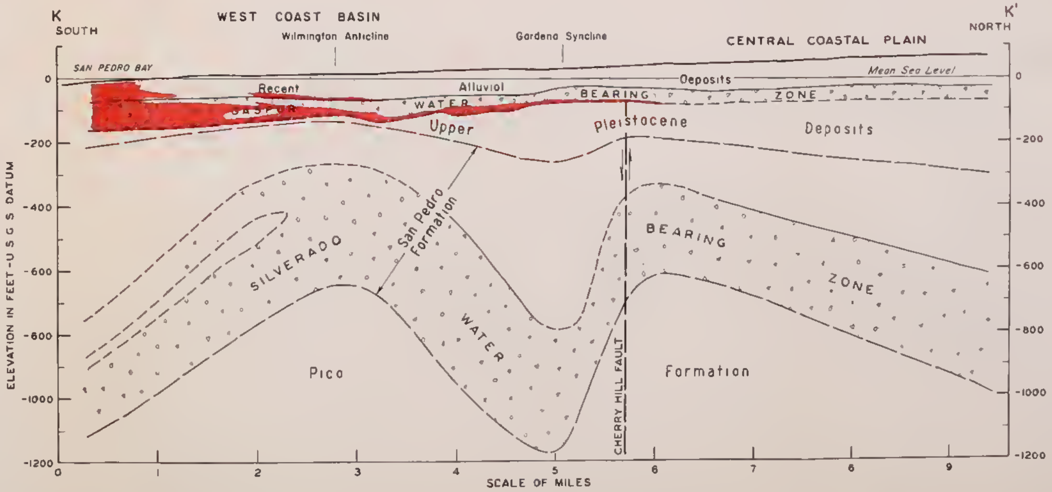


SECTION H-H'
BALLONA GAP TO DOMINGUEZ GAP

NOTE LINES OF GEOLOGIC SECTIONS SHOWN ON PLATE 16



SECTION J-J'
PACIFIC OCEAN TO CENTRAL COASTAL PLAIN



SECTION K-K'
SAN PEDRO BAY TO CENTRAL COASTAL PLAIN

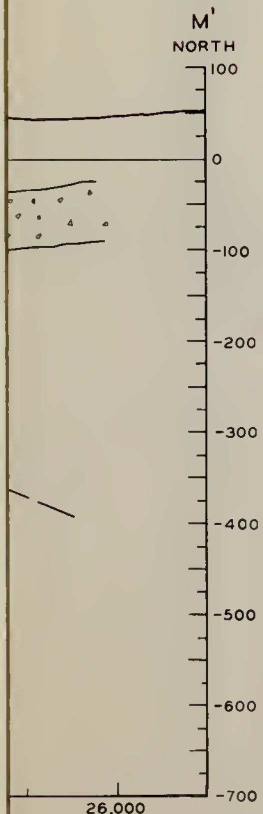
LEGEND

PORTION OF PERMEABLE DEPOSITS CONTAINING GROUND WATER WITH CHLORIDE CONCENTRATION GREATER THAN 100 PARTS PER MILLION

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

GEOLOGIC SECTIONS H-H', J-J', AND K-K' WEST COAST BASIN



LEGEND

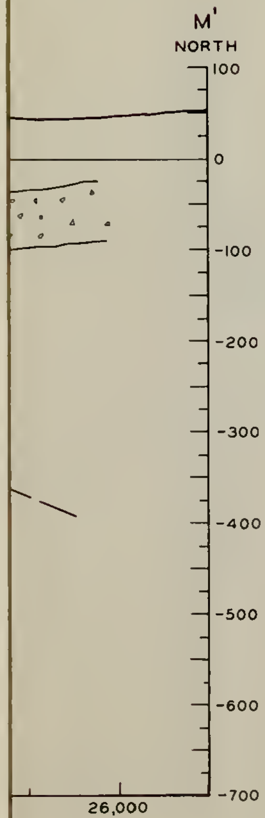
PORTION OF PERMEABLE DEPOSITS CONTAINING GROUND WATER WITH CHLORIDE CONCENTRATION GREATER THAN 100 PARTS PER MILLION

NOTE
LINES OF GEOLOGIC SECTIONS SHOWN ON PLATE 16

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

GEOLOGIC SECTIONS L-L', M-M'
EAST COASTAL PLAIN PRESSURE AREA



LEGEND

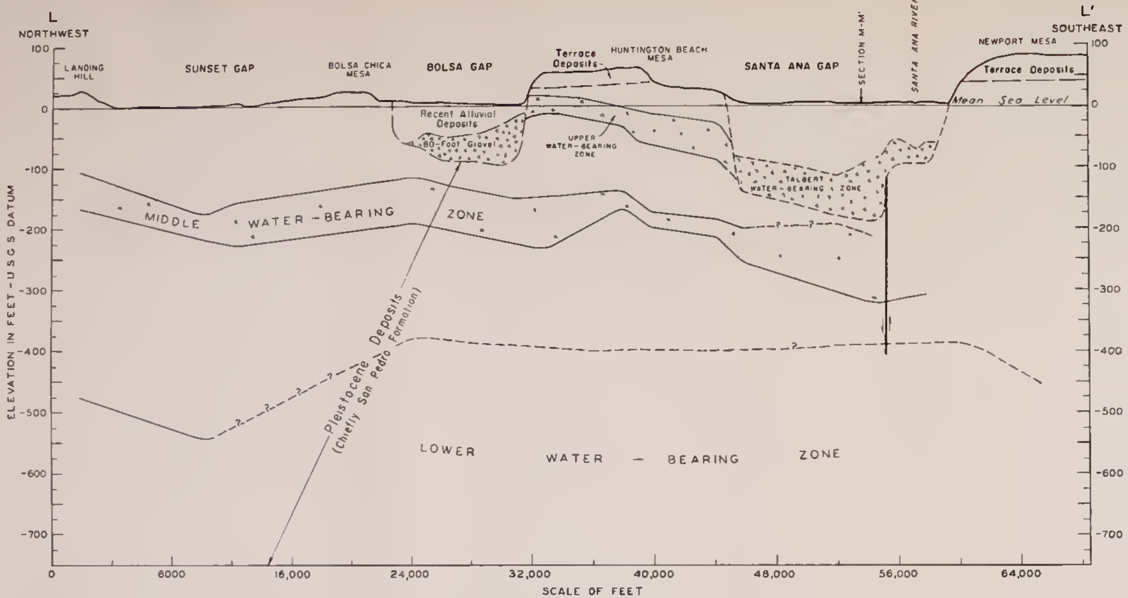
PORTION OF PERMEABLE DEPOSITS CONTAINING GROUND WATER WITH CHLORIDE CONCENTRATION GREATER THAN 100 PARTS PER MILLION

NOTE
LINES OF GEOLOGIC SECTIONS SHOWN ON PLATE 16

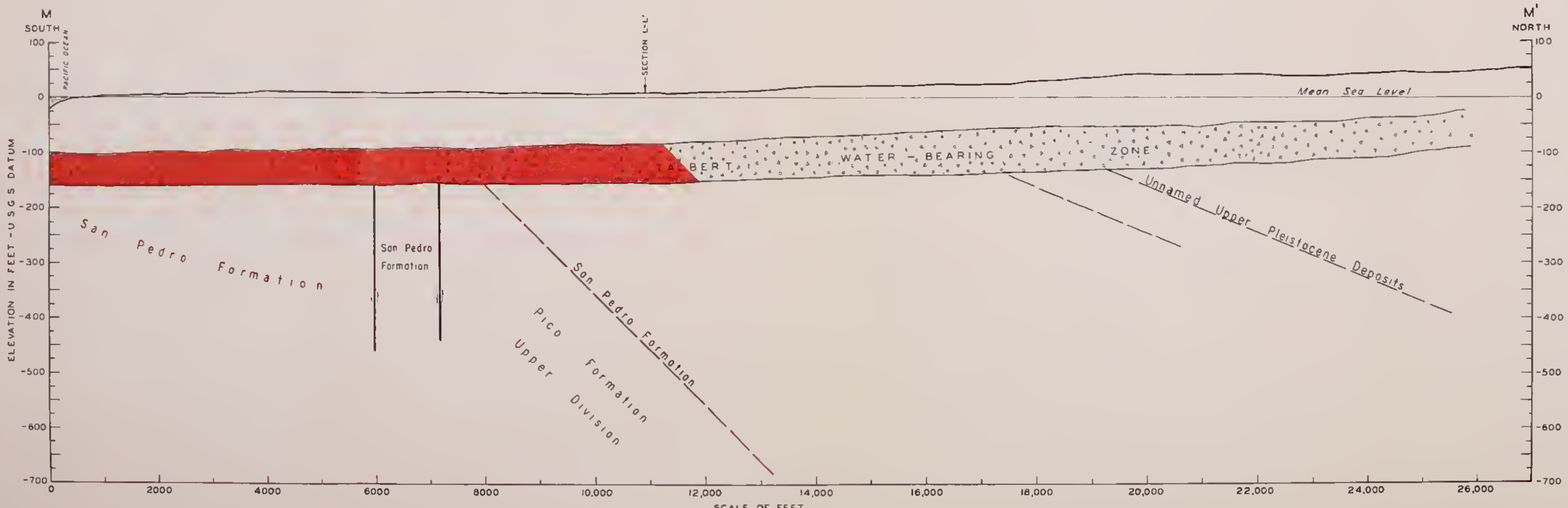
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

GEOLOGIC SECTIONS L-L', M-M'
EAST COASTAL PLAIN PRESSURE AREA



SECTION L-L'
LANDING HILL TO NEWPORT MESA



SECTION M-M'
ALONG AXIS OF SANTA ANA GAP

LEGEND

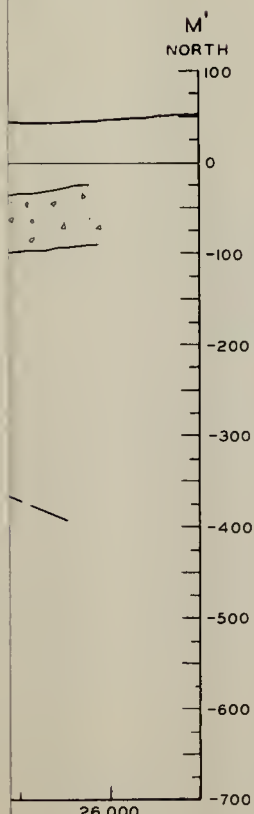
PORTION OF PERMEABLE DEPOSITS CONTAINING GROUND WATER WITH CHLORIDE CONCENTRATION GREATER THAN 100 PARTS PER MILLION

NOTE
LINES OF GEOLOGIC SECTIONS SHOWN ON PLATE 16

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

GEOLOGIC SECTIONS L-L', M-M'
EAST COASTAL PLAIN PRESSURE AREA



LEGEND

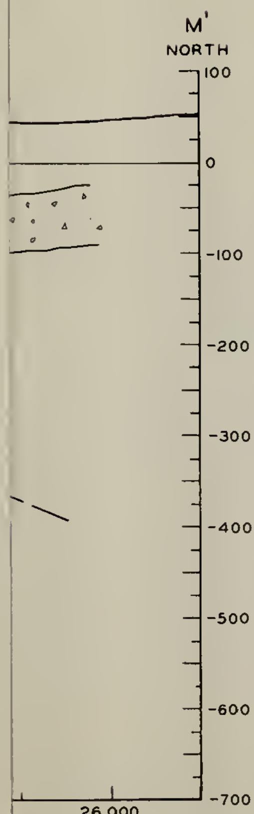
PORTION OF PERMEABLE DEPOSITS CONTAINING GROUND WATER WITH CHLORIDE CONCENTRATION GREATER THAN 100 PARTS PER MILLION

NOTE.
LINES OF GEOLOGIC SECTIONS SHOWN ON PLATE 16

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

GEOLOGIC SECTIONS L-L', M-M'
EAST COASTAL PLAIN PRESSURE AREA



LEGEND

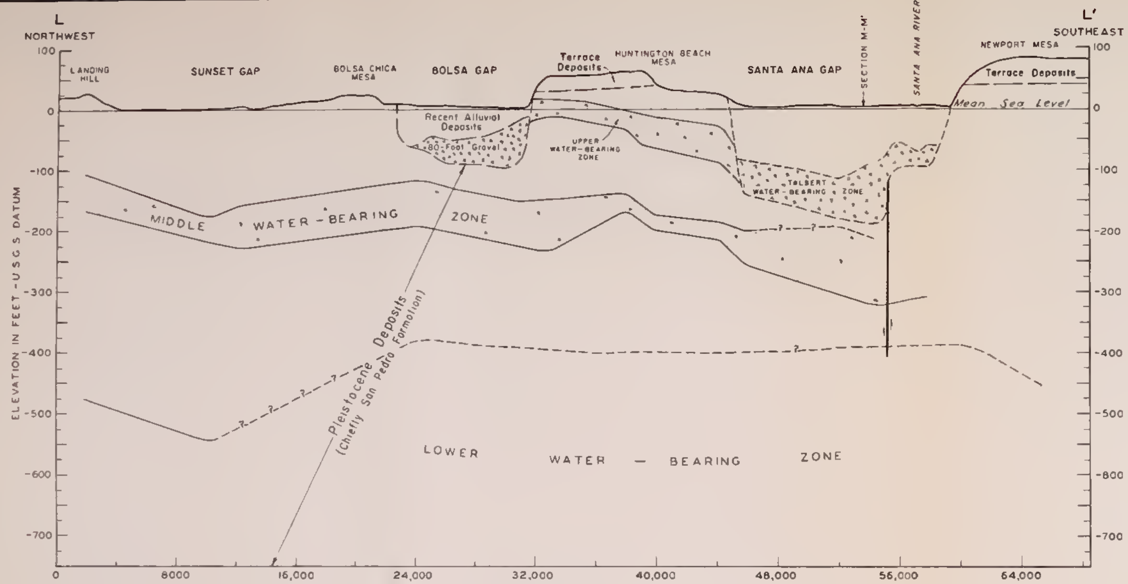
PORTION OF PERMEABLE DEPOSITS CONTAINING GROUND WATER WITH CHLORIDE CONCENTRATION GREATER THAN 100 PARTS PER MILLION

NOTE.
LINES OF GEOLOGIC SECTIONS SHOWN ON PLATE 16

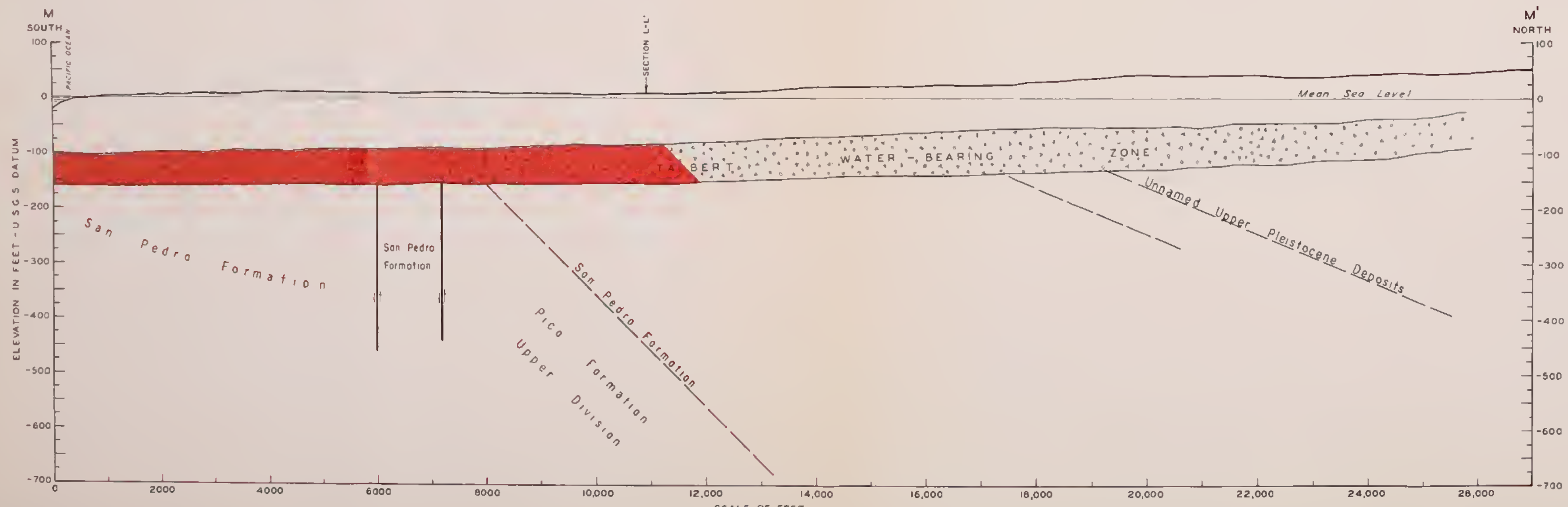
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

GEOLOGIC SECTIONS L-L', M-M'
EAST COASTAL PLAIN PRESSURE AREA



SECTION L-L'
LANDING HILL TO NEWPORT MESA



SECTION M-M'
ALONG AXIS OF SANTA ANA GAP

LEGEND

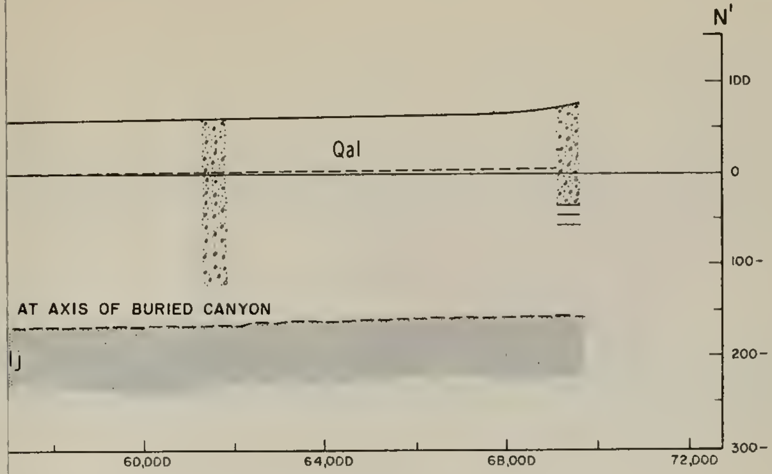
PORTION OF PERMEABLE DEPOSITS CONTAINING GROUND WATER WITH CHLORIDE CONCENTRATION GREATER THAN 100 PARTS PER MILLION

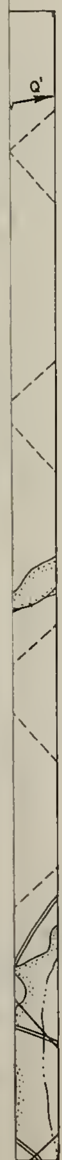
NOTE
LINES OF GEOLOGIC SECTIONS SHOWN ON PLATE 16

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

GEOLOGIC SECTIONS L-L', M-M'
EAST COASTAL PLAIN PRESSURE AREA





LEGEND

RECENT Qal ALLUVIUM AND LAGOONAL DEPOSITS
UNCONSOLIDATED SAND, GRAVEL, AND CLAY

MIOCENE Tso SAN ONOFRE BRECCIA
WELL CEMENTED BOULDERS, COBBLES, PEBBLES, AND SAND

EOCENE Tlj LA JOLLA FORMATION
CONSOLIDATED SAND, CLAY, AND SHALE

EXTENT OF SEA WATER INTRUSION
(Chlorides exceed 100 ppm)
Data as of January 1956

VALLEY AREAS

O O' LINE OF GEOLOGIC SECTION

—0— LINE OF ZERO GROUND WATER ELEVATION

AXIS OF PUMPING TROUGH

WATER WELL

SURFACE WATER SAMPLING POINT

TYPICAL WELL

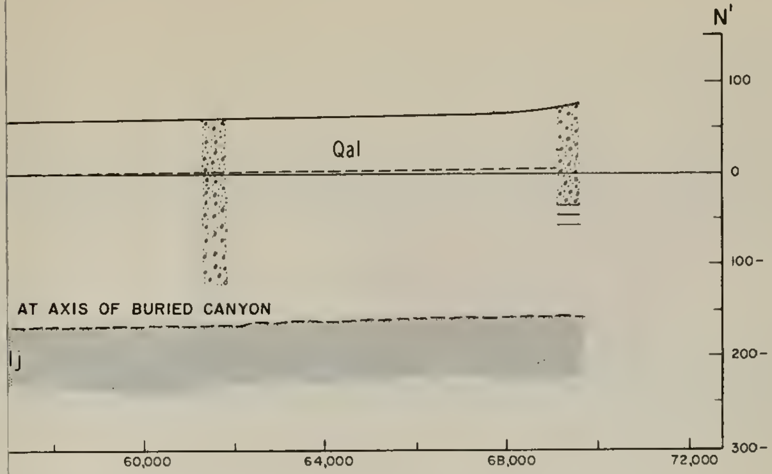
HIGHLY PERMEABLE
INCLUDES UNCONSOLIDATED SANDS AND GRAVEL

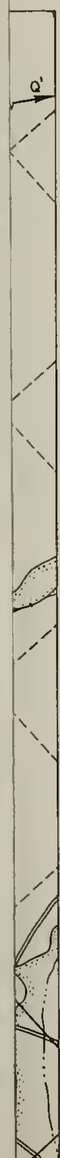
SLIGHTLY PERMEABLE
INCLUDES SILT AND FINE SANDS

IMPERMEABLE
INCLUDES CLAY AND CEMENTED SANDSTONES

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

STATUS OF SEA-WATER INTRUSION AND GEOLOGIC SECTIONS N-N', O-O', P-P', AND Q-Q' MISSION BASIN





LEGEND

RECENT	Qal	ALLUVIUM AND LAGOONAL DEPOSITS UNCONSOLIDATED SAND, GRAVEL, AND CLAY
MIOCENE	Tso	SAN ONOFRE BRECCIA WELL CEMENTED BOULDERS, COBBLES, PEBBLES, AND SAND
EOCENE	Tlj	LA JOLLA FORMATION CONSOLIDATED SAND, CLAY, AND SHALE

EXTENT OF SEA WATER INTRUSION
(Chlorides exceed 100 ppm)
Data as of January 1956

VALLEY AREAS

O O' LINE OF GEOLOGIC SECTION

—O— LINE OF ZERO GROUND WATER ELEVATION

AXIS OF PUMPING TROUGH

WATER WELL

SURFACE WATER SAMPLING POINT

TYPICAL WELL

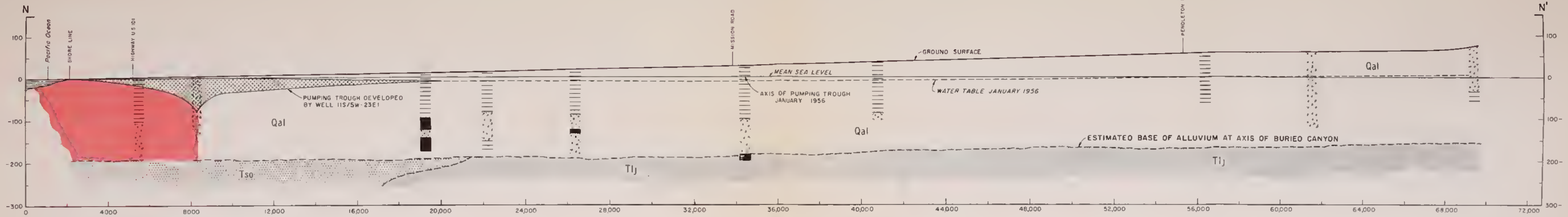
HIGHLY PERMEABLE
INCLUDES UNCONSOLIDATED SANDS AND GRAVEL

SLIGHTLY PERMEABLE
INCLUDES SILT AND FINE SANDS

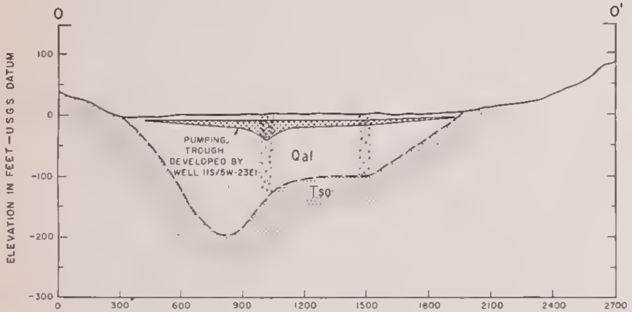
IMPERMEABLE
INCLUDES CLAY AND CEMENTED SANDSTONES

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

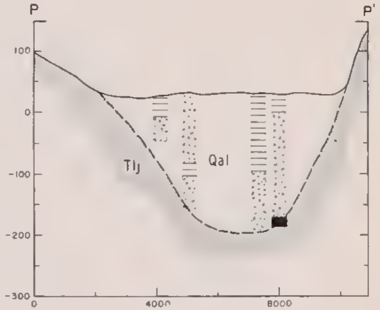
STATUS OF SEA-WATER INTRUSION
AND
GEOLOGIC SECTIONS N-N', O-O', P-P', AND Q-Q'
MISSION BASIN



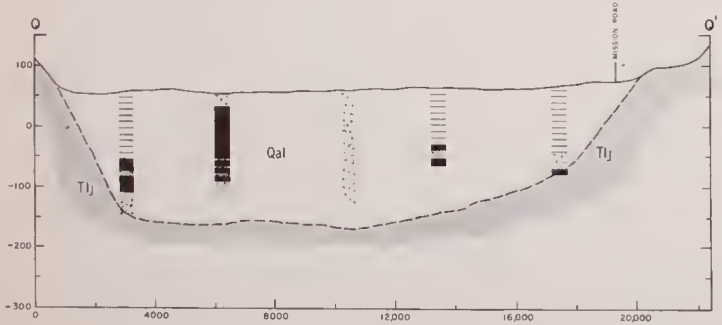
SECTION N-N'
THROUGH SAN LUIS REY RIVER CANYON AND MISSION BASIN



SECTION O-O'
ACROSS SAN LUIS REY CANYON

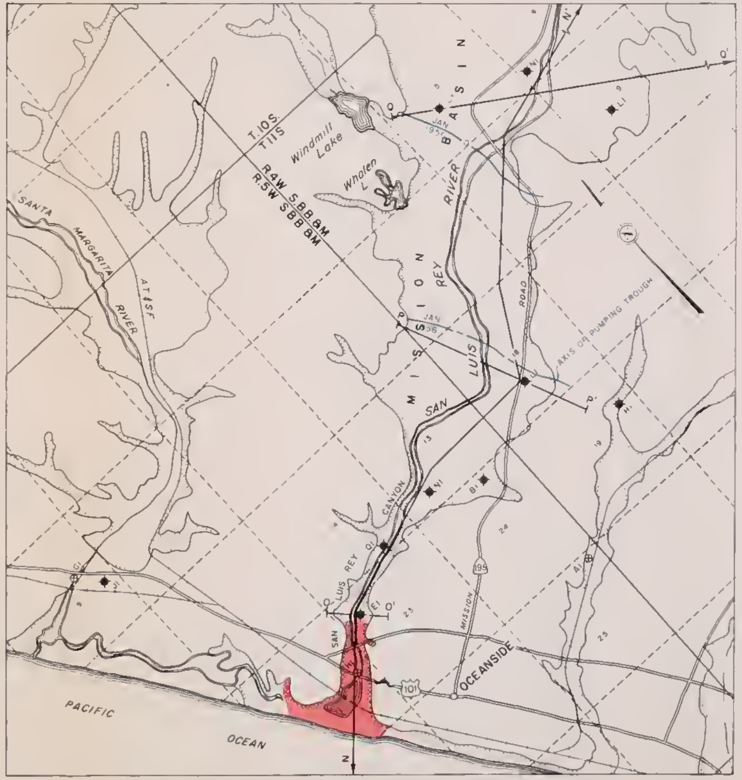


SECTION P-P'
ACROSS MISSION BASIN



SECTION Q-Q'
ACROSS MISSION BASIN

LOCATION MAP



MISSION BASIN

LEGEND

RECENT	Qal	ALLUVIUM AND LAGOONAL DEPOSITS UNCONSOLIDATED SAND, GRAVEL, AND CLAY
MIOCENE	Tso	SAN ONOFRE BRECCIA WELL CEMENTED BOULDERS, COBBLES, PEBBLES, AND SAND
EOCENE	Tlj	LA JOLLA FORMATION CONSOLIDATED SAND, CLAY, AND SHALE

EXTENT OF SEA WATER INTRUSION (Chlorides exceed 100 ppm) Data as of January 1956

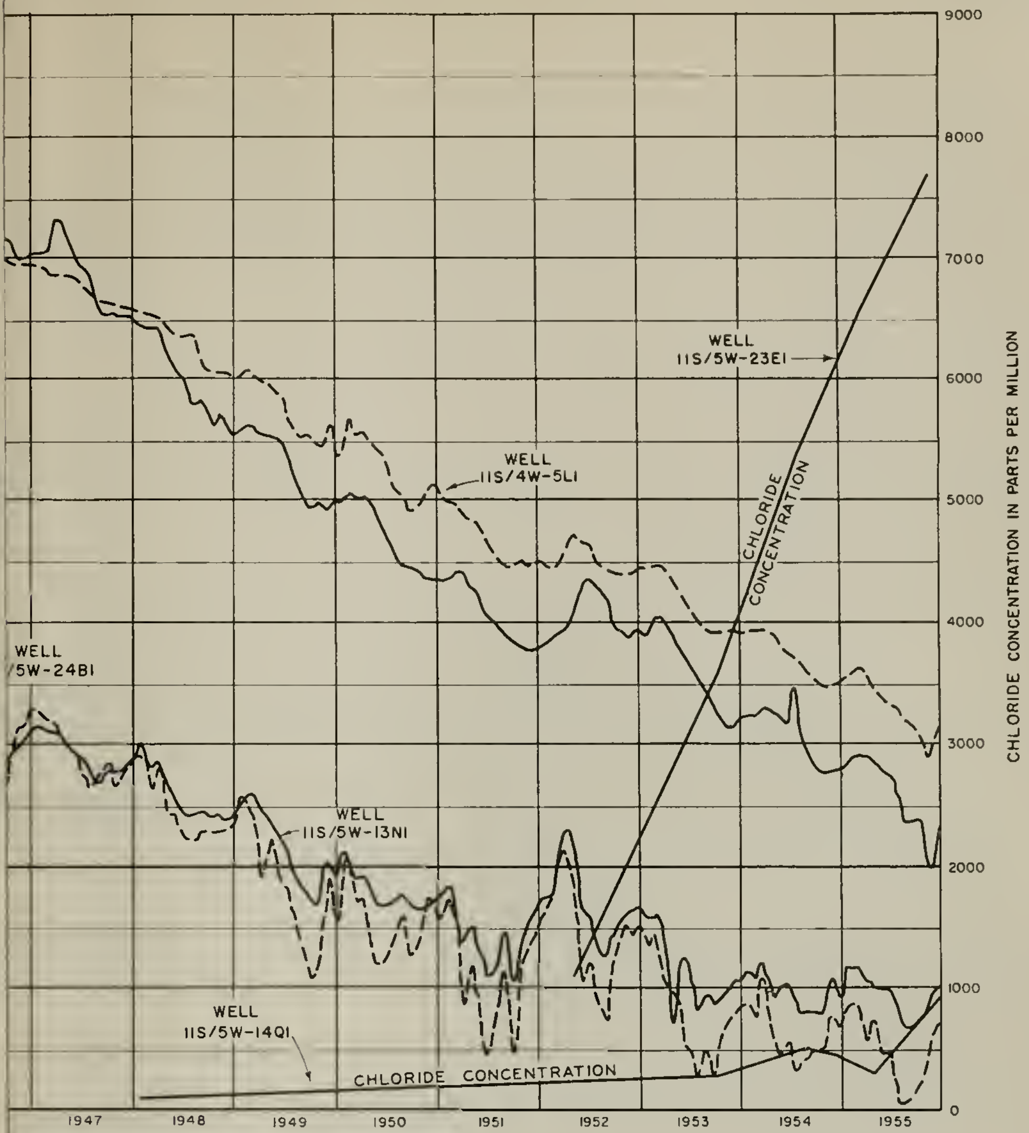
VALLEY AREAS
LINE OF GEOLOGIC SECTION
LINE OF ZERO GROUND WATER ELEVATION
AXIS OF PUMPING TROUGH
WATER WELL
SURFACE WATER SAMPLING POINT

TYPICAL WELL

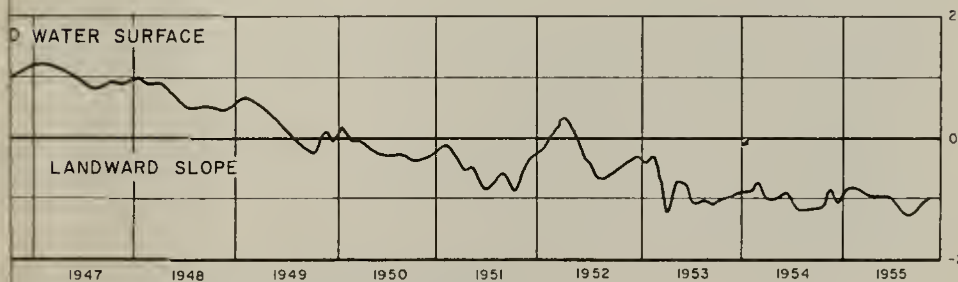
HIGHLY PERMEABLE INCLUDES UNCONSOLIDATED SANDS AND GRAVEL
SLIGHTLY PERMEABLE INCLUDES SILT AND FINE SANDS
IMPERMEABLE INCLUDES CLAY AND CEMENTED SANDSTONES

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

STATUS OF SEA-WATER INTRUSION AND GEOLOGIC SECTIONS N-N', O-O', P-P', AND Q-Q' MISSION BASIN



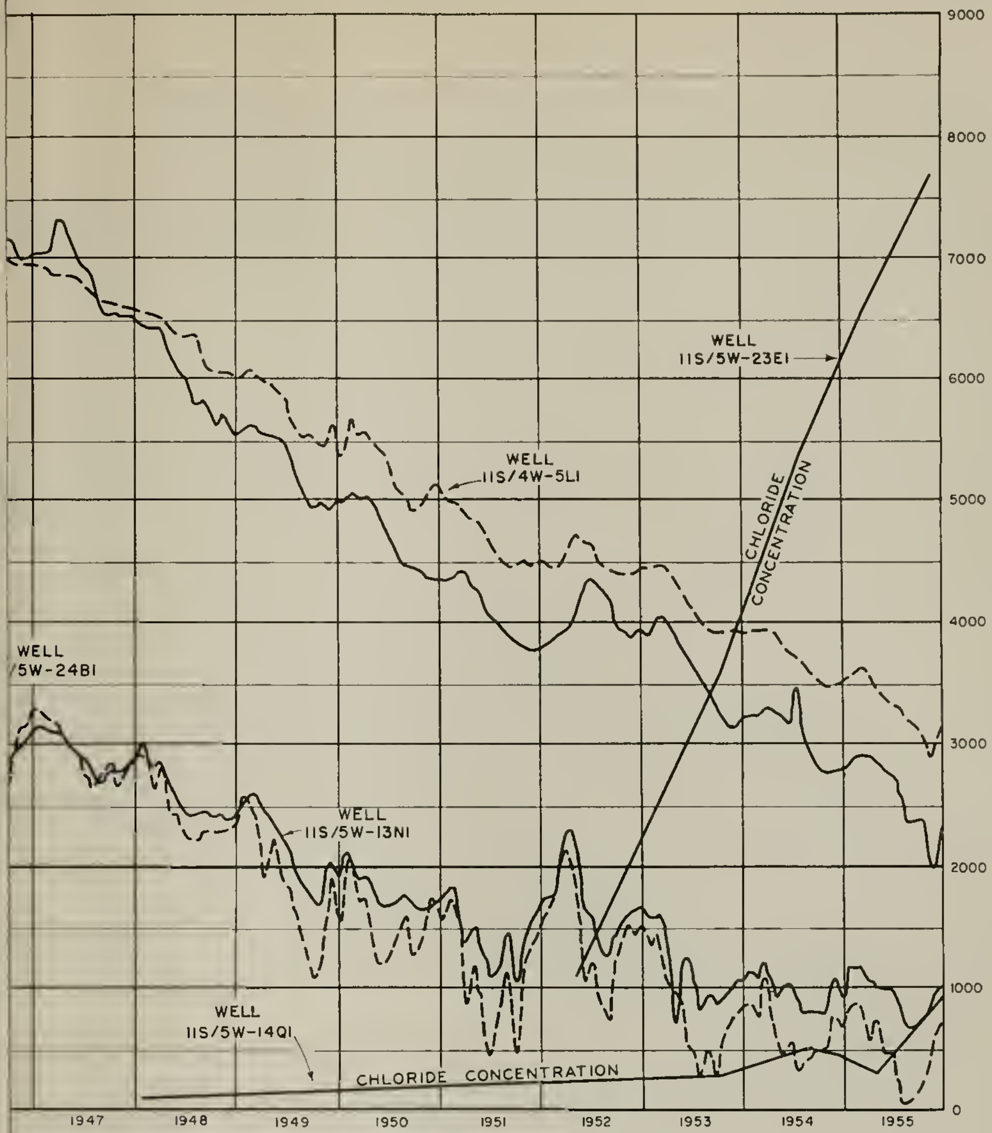
ON AND WATER LEVEL FLUCTUATIONS



EN WELL 11S/5W-13N1 AND SHORELINE

E CONCENTRATION

UATIONS IN WELLS
BASIN

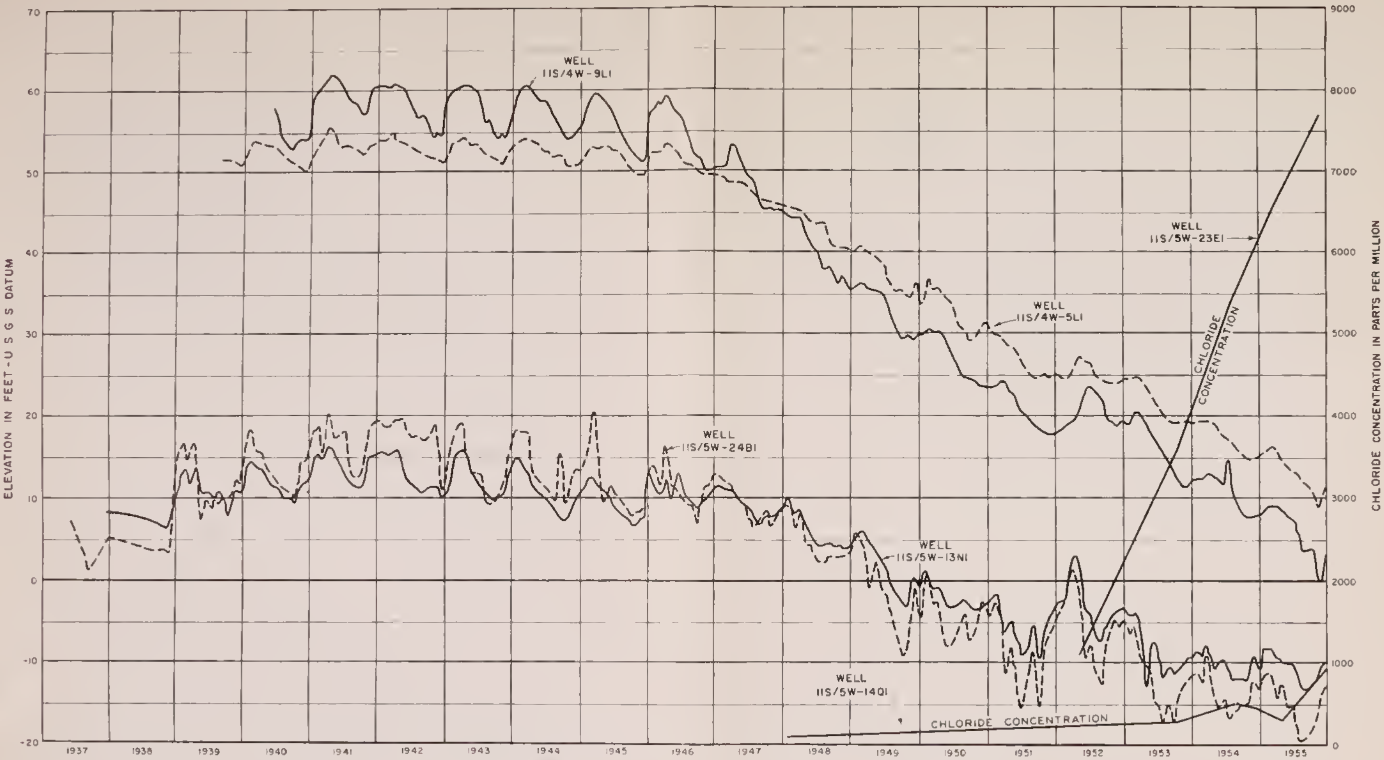


ON AND WATER LEVEL FLUCTUATIONS

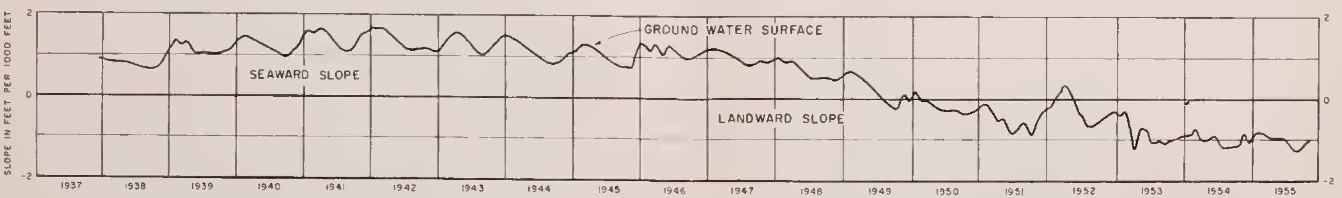
EEN WELL 11S/5W-13N1 AND SHORELINE

E CONCENTRATION

TUATIONS IN WELLS
BASIN

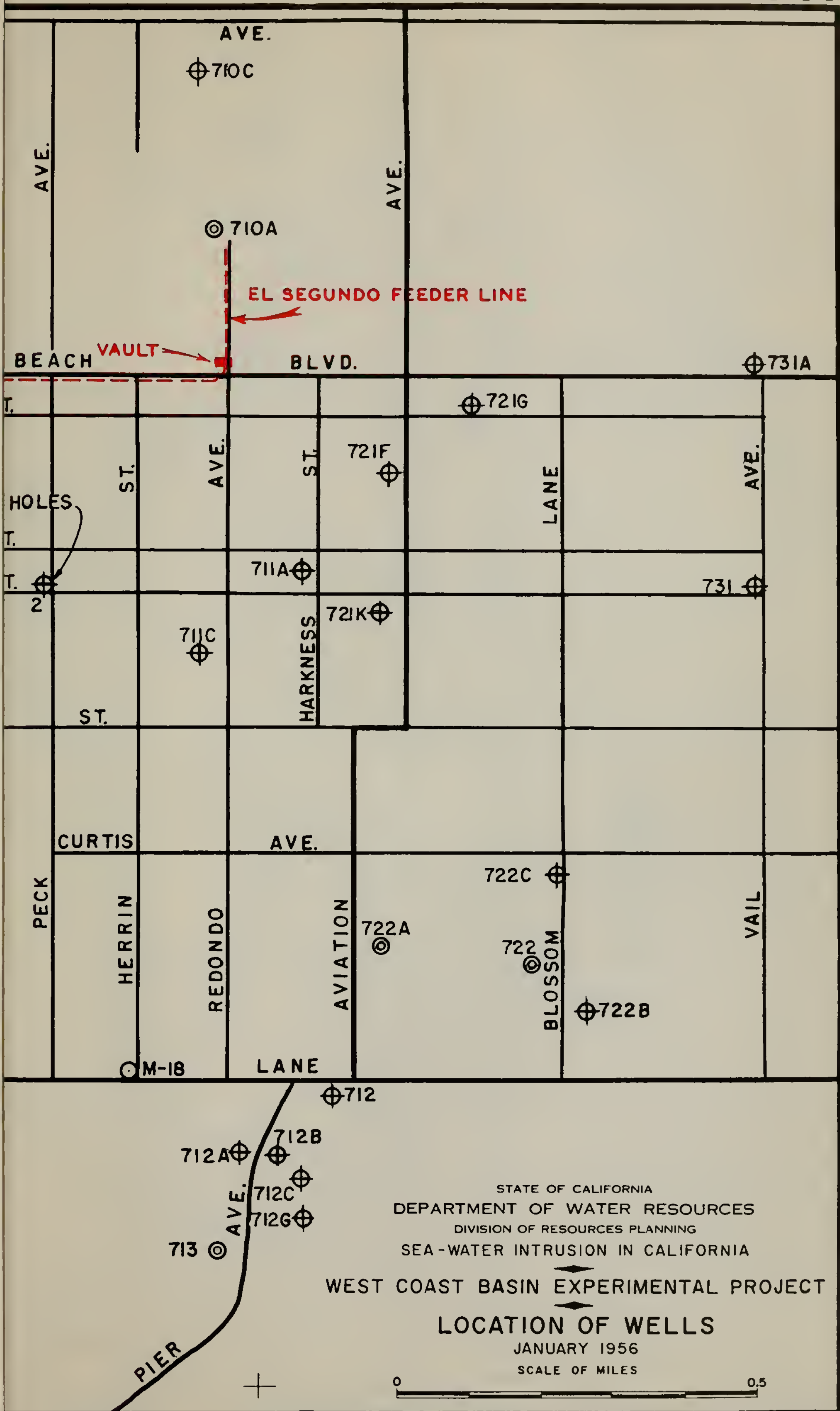


CHANGES IN CHLORIDE CONCENTRATION AND WATER LEVEL FLUCTUATIONS



SLOPE OF GROUND WATER SURFACE BETWEEN WELL 11S/5W-13N1 AND SHORELINE

CHANGES IN CHLORIDE CONCENTRATION
AND
WATER LEVEL FLUCTUATIONS IN WELLS
MISSION BASIN



STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

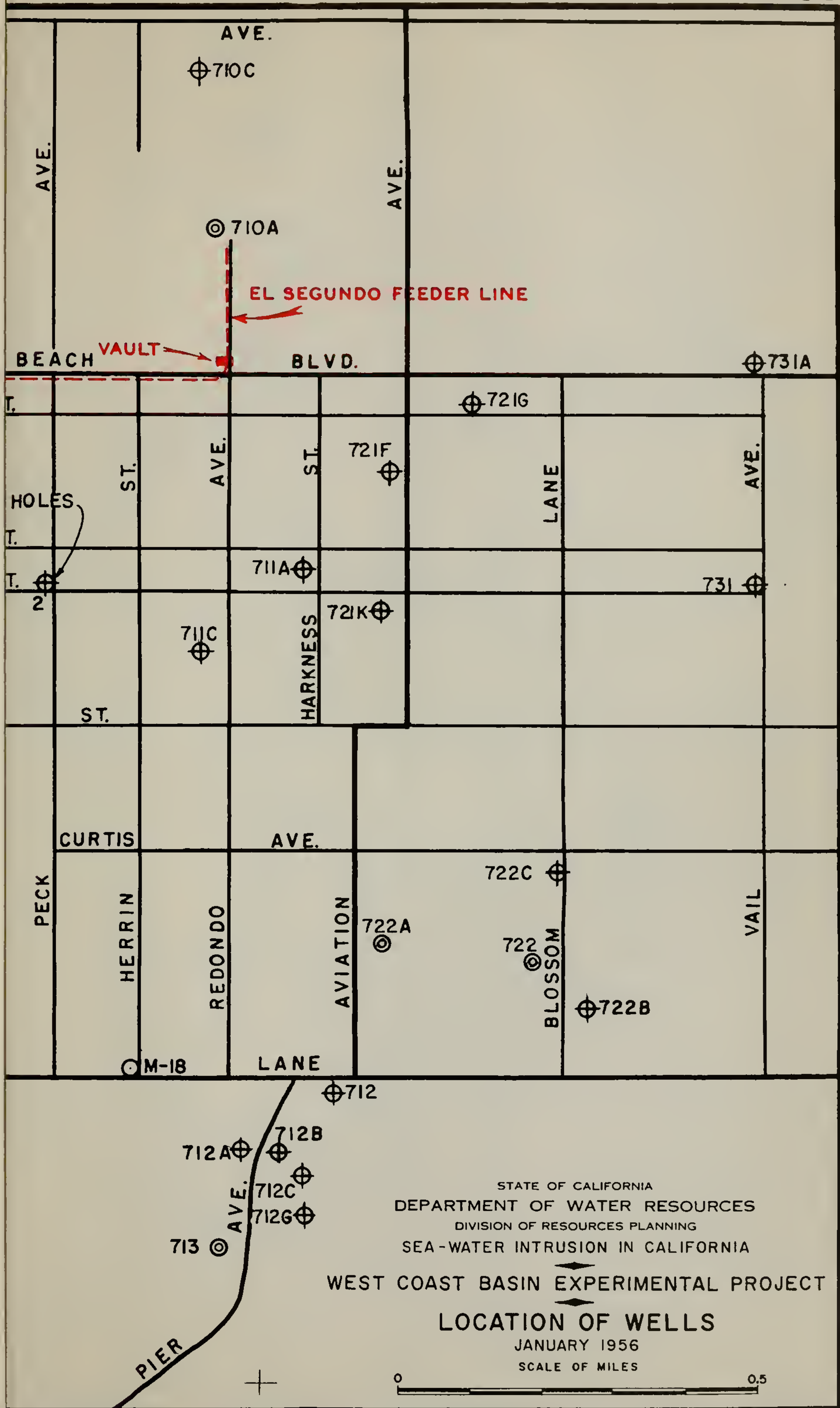
WEST COAST BASIN EXPERIMENTAL PROJECT

LOCATION OF WELLS

JANUARY 1956

SCALE OF MILES

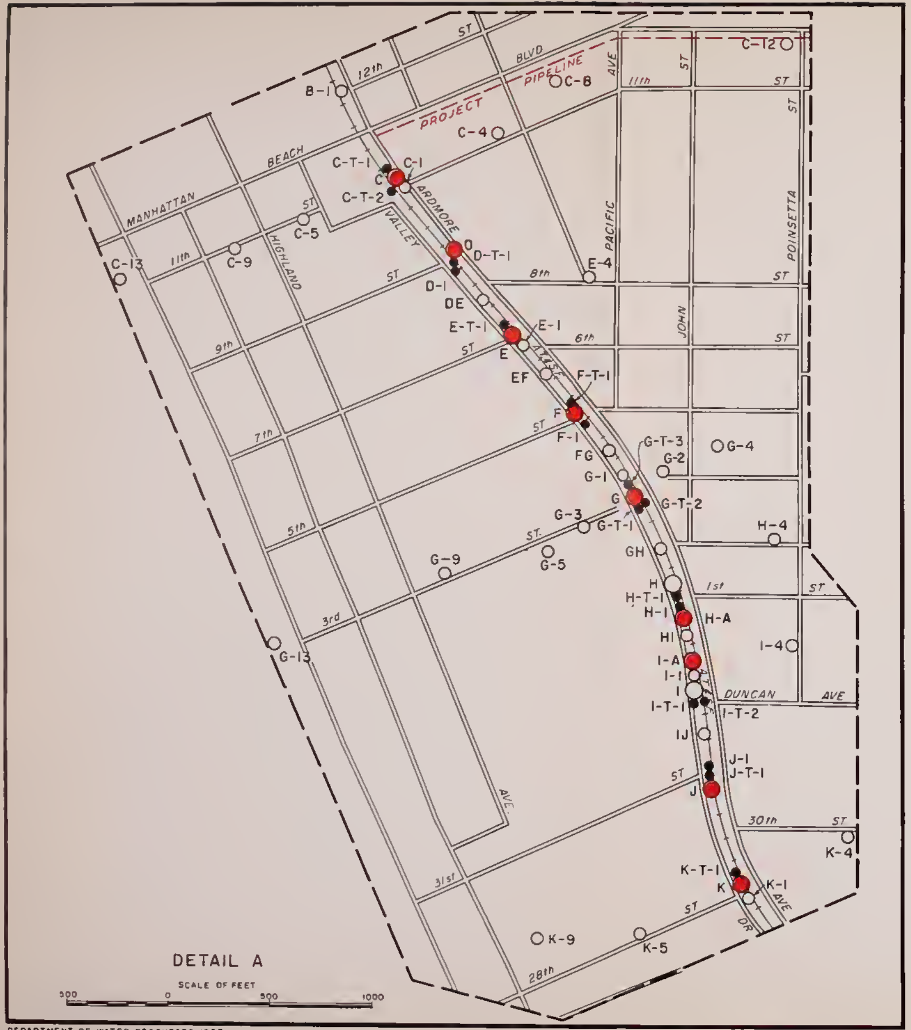
0 — 0.5

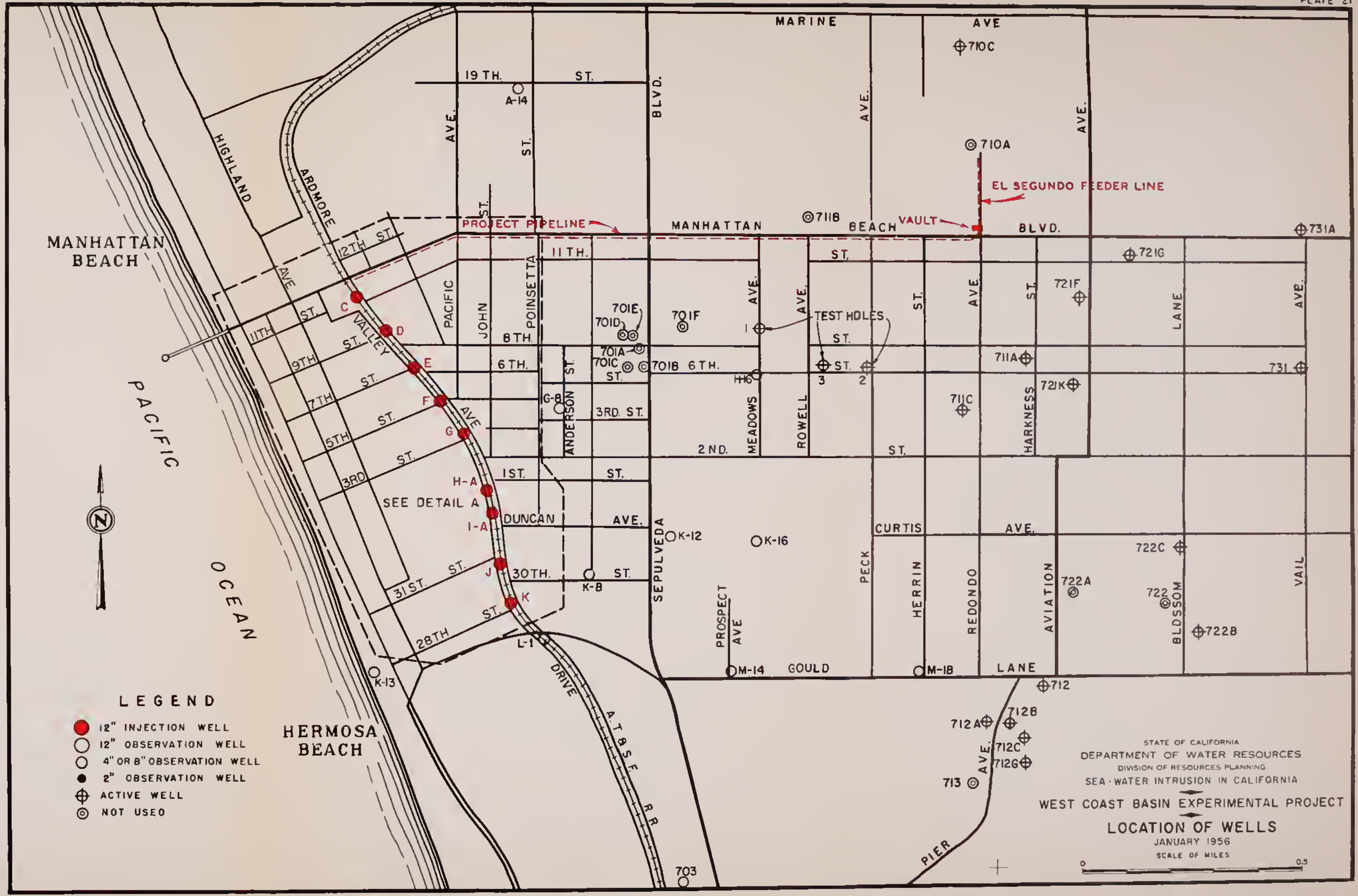


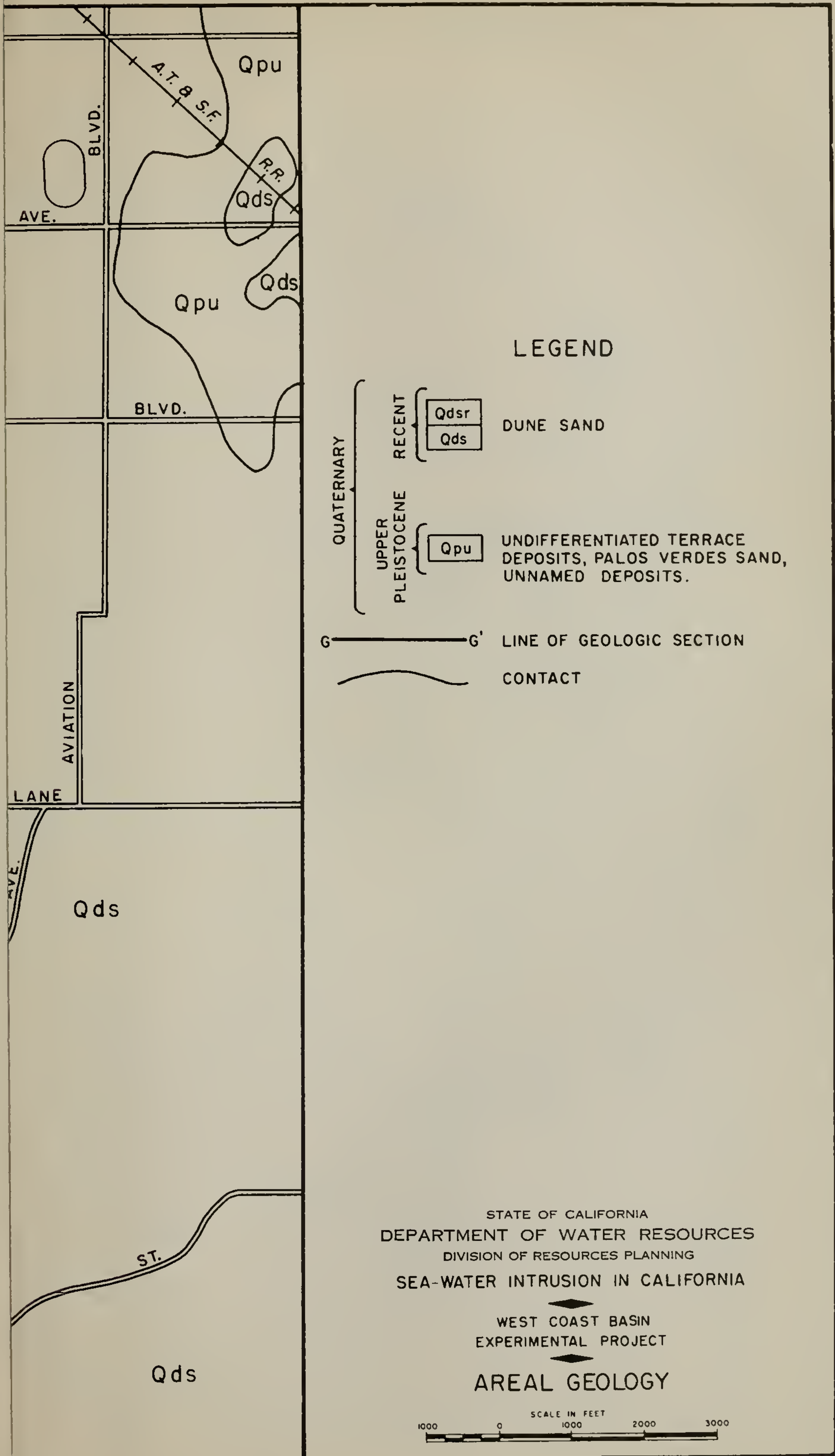
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

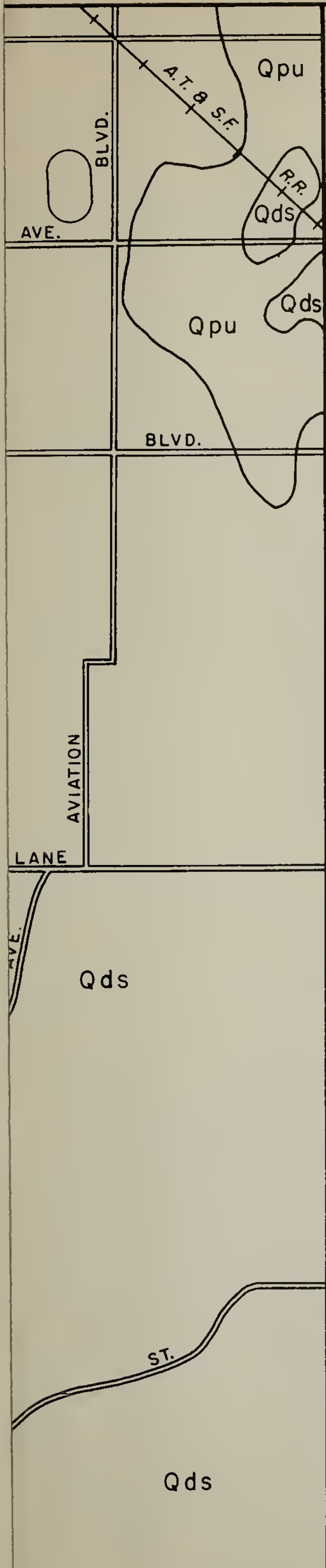
WEST COAST BASIN EXPERIMENTAL PROJECT

LOCATION OF WELLS
JANUARY 1956
SCALE OF MILES
0 — 0.5


DETAIL A
SCALE OF FEET
500 0 500 1000
PROJECT PIPELINE
MANHATTAN
BEACH
BLVD
12th
11th
9th
7th
5th
3rd
31st
28th
ARDMORE
VALLEY
HIGHLAND
PACIFIC
JOHN
POINSETTA
DUNCAN AVE
30th ST
1st ST
8th ST
6th ST
B-1
C-12
C-8
C-4
C-T-1
C-1
C-T-2
C-5
C-9
C-13
D-T-1
D-1
DE
E-T-1
E-1
E-4
EF
F-T-1
F-1
FG
G-T-3
G-2
G-4
G-1
G-T-2
G-3
G-T-1
G-9
G-5
GH
H-4
H-T-1
H-1
H-A
HI
I-4
I-A
I-1
I-T-1
I-T-2
IJ
J-1
J-T-1
G-13
K-4
K-T-1
K-1
K-9
K-5


MARINE AVE
19TH. ST.
MANHATTAN BEACH BLVD.
EL SEGUNDO FEEDER LINE
PROJECT PIPELINE
VAULT
MANHATTAN
BEACH
PACIFIC
OCEAN
HERMOSA
BEACH
HIGHLAND
ARDMORE
VALLEY
SEE DETAIL A
DUNCAN AVE.
30TH. ST.
GOULD LANE
SEPULVEDA
PROSPECT AVE
MEADOWS
ROWELL
PECK
HERRIN
REDONDO
AVIATION
BLOSSOM
HARKNESS
LANE
VAIL
CURTIS AVE.
TEST HOLES
A.T.&S.F. R.R.
DRIVE
PIER
N
A-14
710C
710A
711B
731A
721G
721F
701E
701D
701F
701A
701C
701B
711A
731
721K
711C
722C
722A
722
722B
712
712A
712B
712C
712G
713
703
K-12
K-16
K-8
K-13
L-1
M-14
M-18
G-8
LEGEND
12" INJECTION WELL
12" OBSERVATION WELL
4" OR 8" OBSERVATION WELL
2" OBSERVATION WELL
ACTIVE WELL
NOT USED
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA
WEST COAST BASIN EXPERIMENTAL PROJECT
LOCATION OF WELLS
JANUARY 1956
SCALE OF MILES
0 0.5


Qpu
A.T. & S.F.
BLVD.
R.R.
Qds
AVE.
Qds
Qpu
BLVD.
AVIATION
LANE
AVE.
Qds
ST.
Qds
LEGEND
QUATERNARY
RECENT
Qdsr
Qds
DUNE SAND
UPPER PLEISTOCENE
Qpu
UNDIFFERENTIATED TERRACE DEPOSITS, PALOS VERDES SAND, UNNAMED DEPOSITS.
G G'
LINE OF GEOLOGIC SECTION
CONTACT
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA
WEST COAST BASIN
EXPERIMENTAL PROJECT
AREAL GEOLOGY
SCALE IN FEET
1000
0
1000
2000
3000



LEGEND

QUATERNARY

RECENT

Qdsr / Qds	DUNE SAND

UPPER PLEISTOCENE

Qpu	UNDIFFERENTIATED TERRACE DEPOSITS, PALOS VERDES SAND, UNNAMED DEPOSITS.

G———G' LINE OF GEOLOGIC SECTION

CONTACT

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

WEST COAST BASIN
EXPERIMENTAL PROJECT

AREAL GEOLOGY

SCALE IN FEET
1000 0 1000 2000 3000

LEGEND

QUATERNARY

RECENT — Qdsr, Qds — DUNE SAND

UPPER PLEISTOCENE — Qpu — UNDIFFERENTIATED TERRACE DEPOSITS, PALOS VERDES SAND, UNNAMED DEPOSITS.

G——G' LINE OF GEOLOGIC SECTION

CONTACT

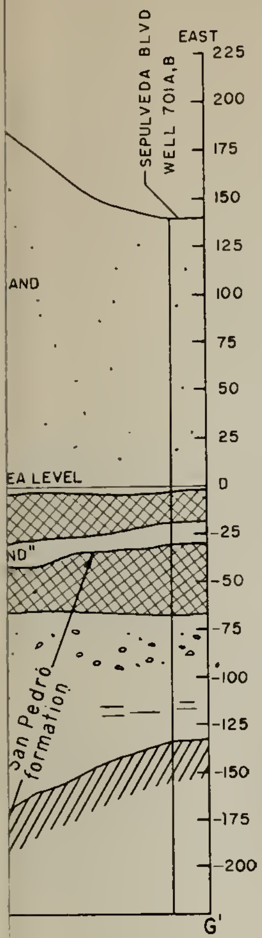
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

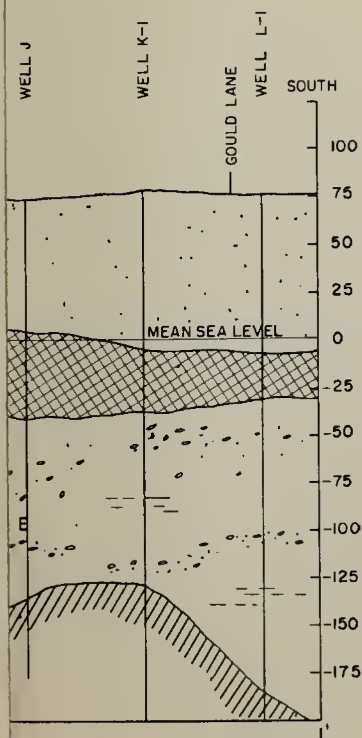
SEA-WATER INTRUSION IN CALIFORNIA

WEST COAST BASIN
EXPERIMENTAL PROJECT

AREAL GEOLOGY

SCALE IN FEET
1000 0 1000 2000 3000





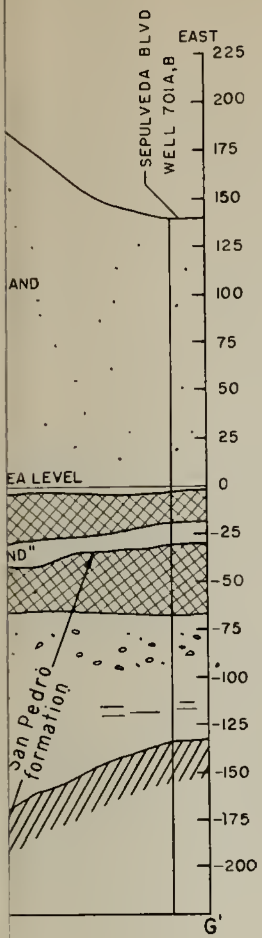
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

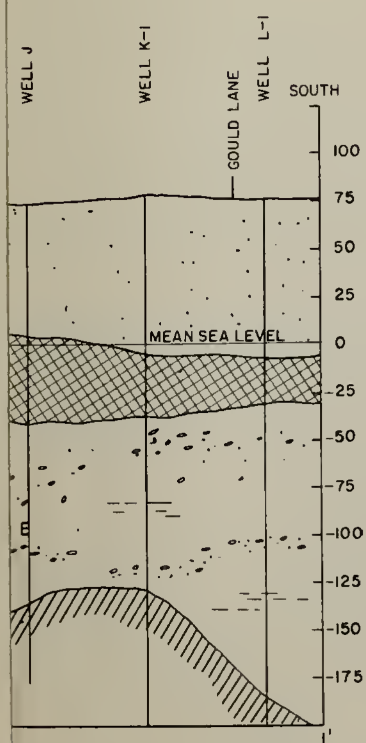
SEA-WATER INTRUSION IN CALIFORNIA

WEST COAST BASIN EXPERIMENTAL PROJECT

GEOLOGIC SECTIONS
G-G' AND I-I'

HORIZONTAL SCALE
SCALE 500 0 500 1000 FEET





STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

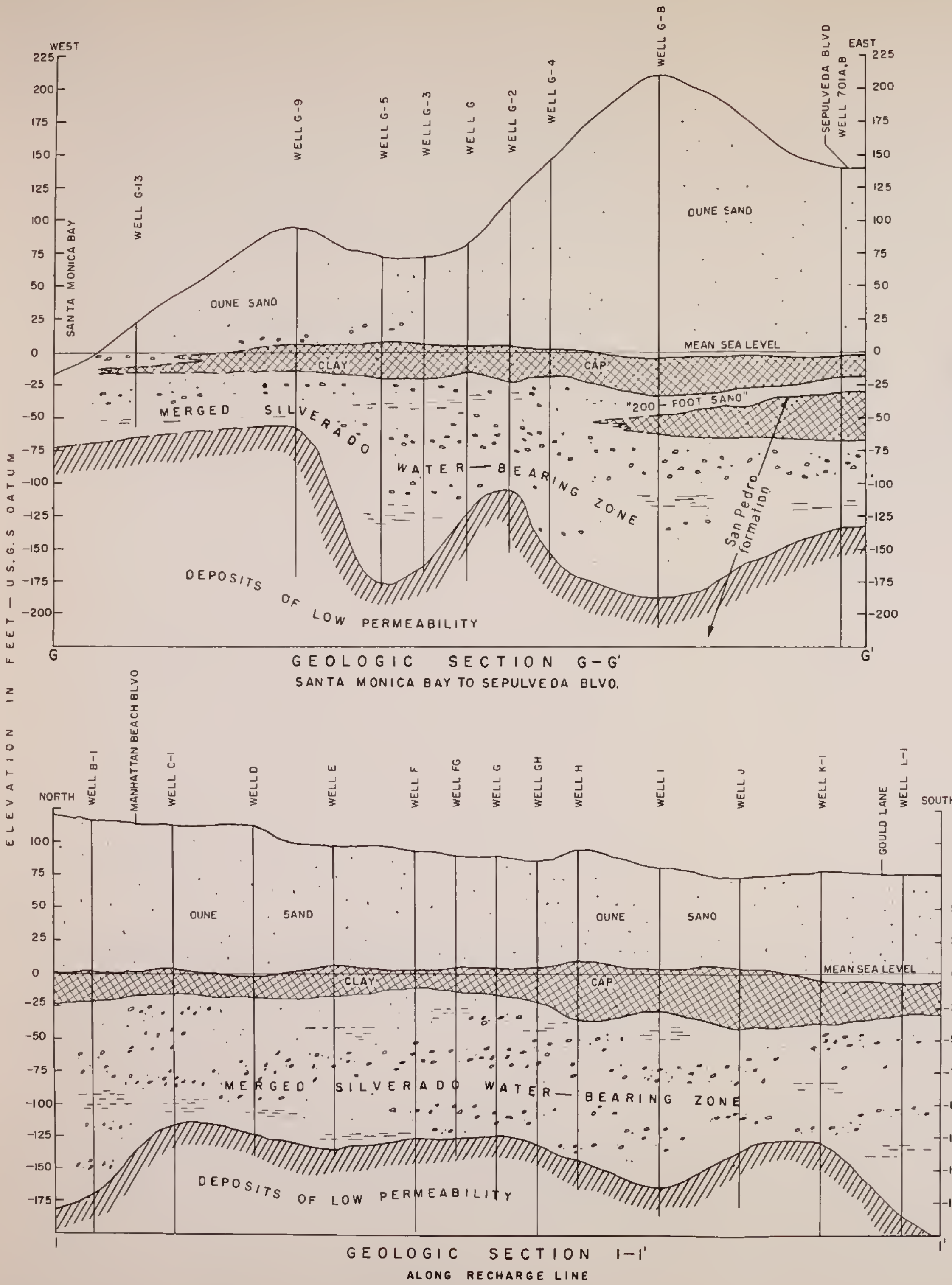
SEA-WATER INTRUSION IN CALIFORNIA

WEST COAST BASIN EXPERIMENTAL PROJECT

GEOLOGIC SECTIONS
G-G' AND I-I'

HORIZONTAL SCALE

SCALE 500 0 500 1000 FEET



STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

WEST COAST BASIN EXPERIMENTAL PROJECT

GEOLOGIC SECTIONS
G-G' AND I-I'

HORIZONTAL SCALE
SCALE 500 0 500 1000 FEET

DEPARTMENT OF WATER RESOURCES 1957

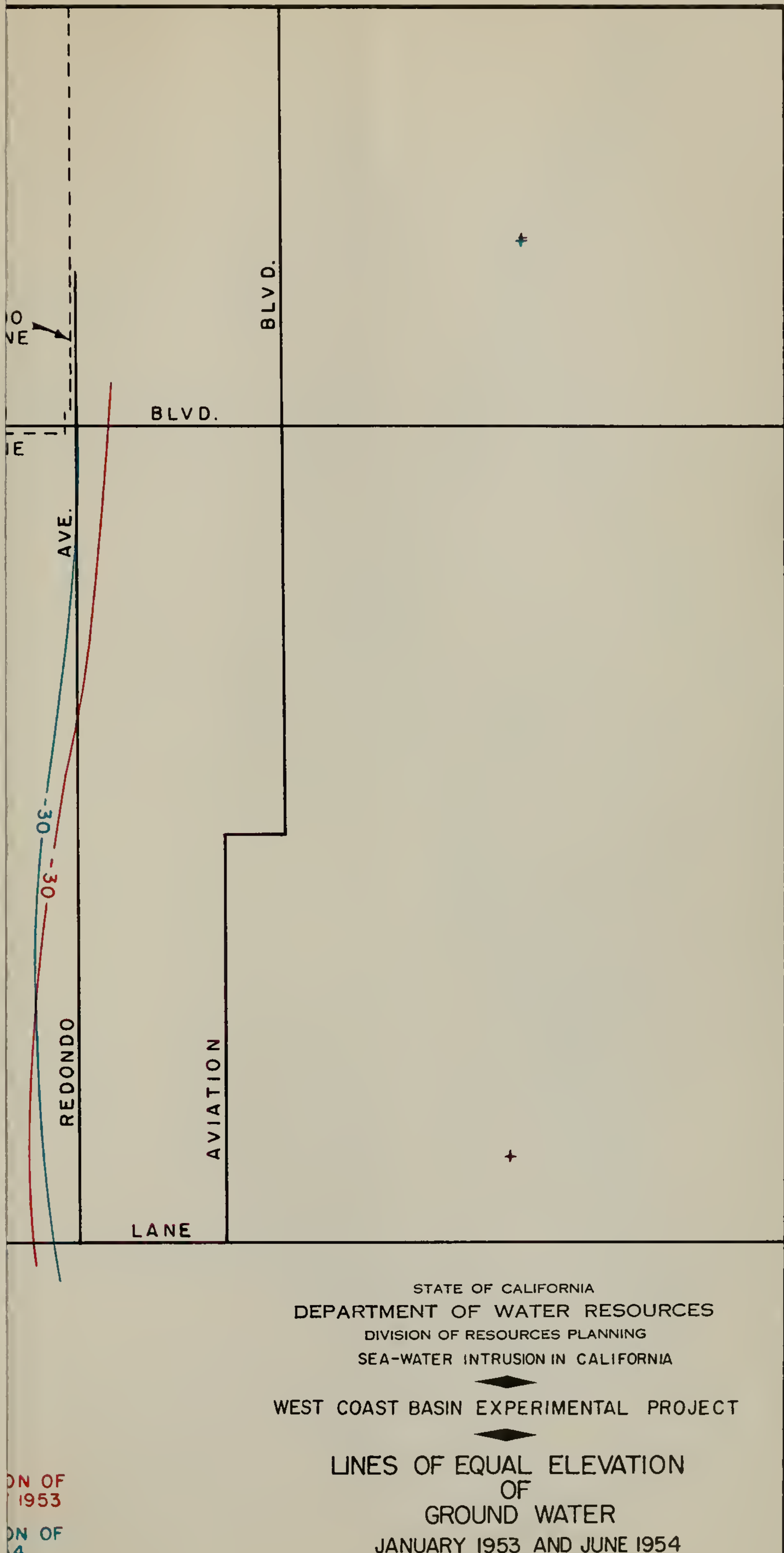
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

WEST COAST BASIN EXPERIMENTAL PROJECT

LINES OF EQUAL ELEVATION
OF
GROUND WATER
JANUARY 1953 AND JUNE 1954

SCALE OF MILES 0 1/4

86952-C



STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

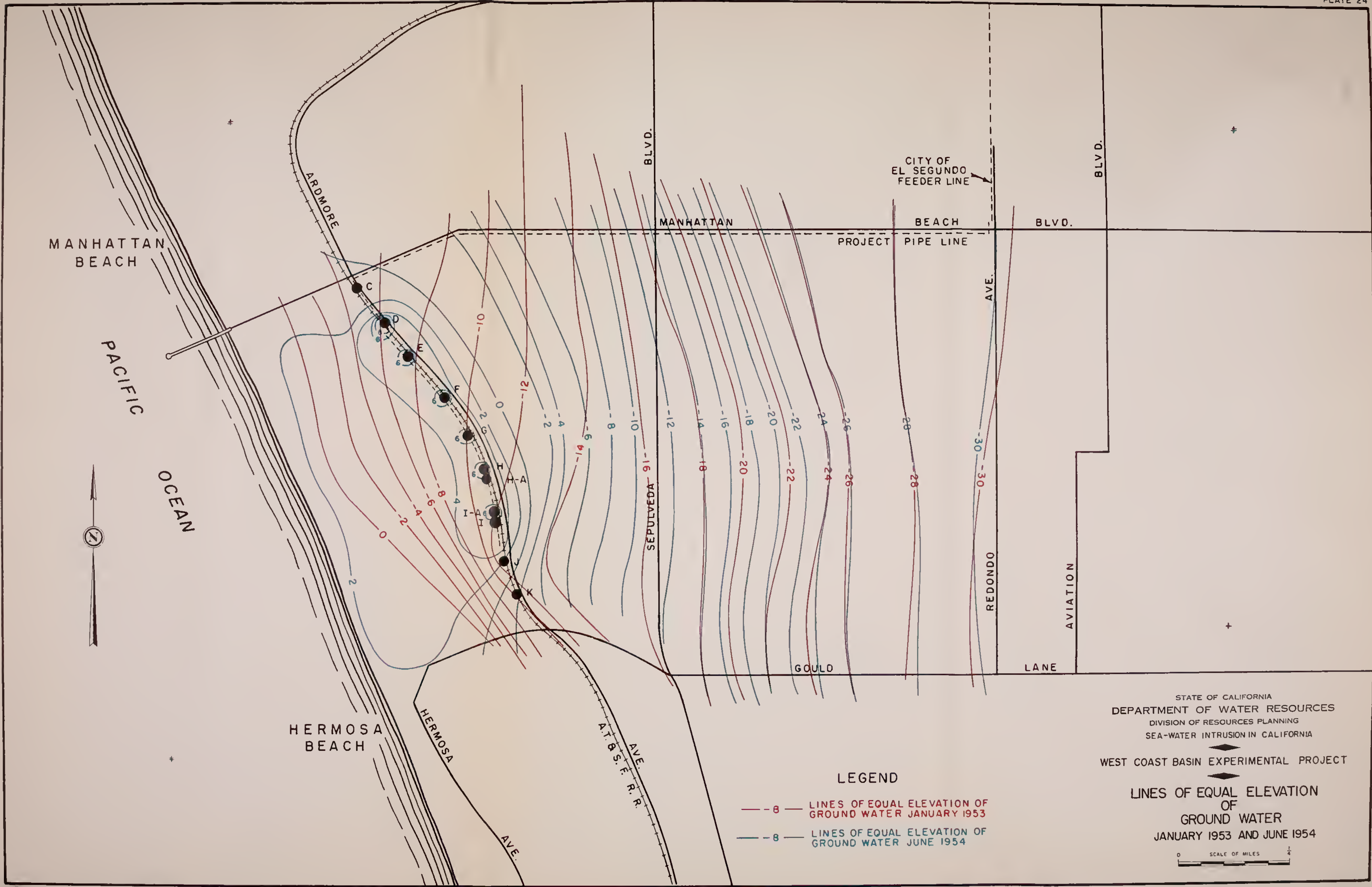
WEST COAST BASIN EXPERIMENTAL PROJECT

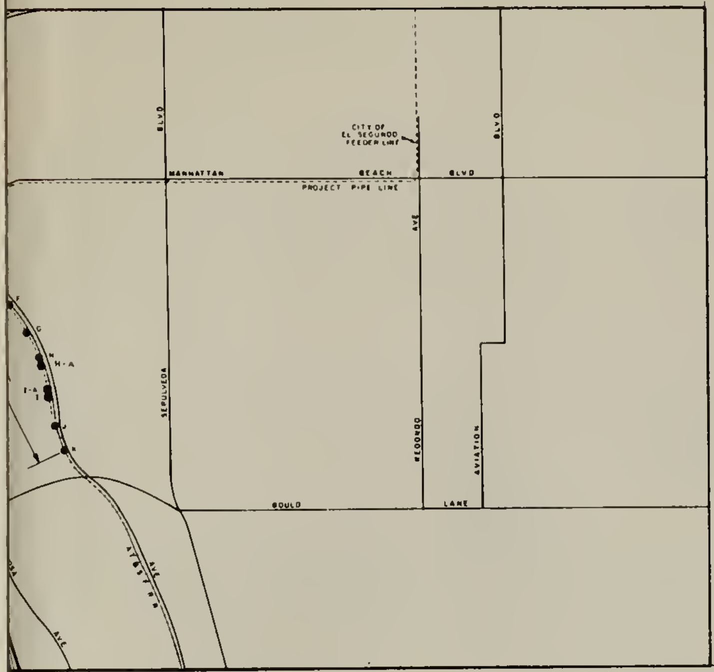
LINES OF EQUAL ELEVATION OF GROUND WATER

JANUARY 1953 AND JUNE 1954

0 SCALE OF MILES 1/4

86952-C

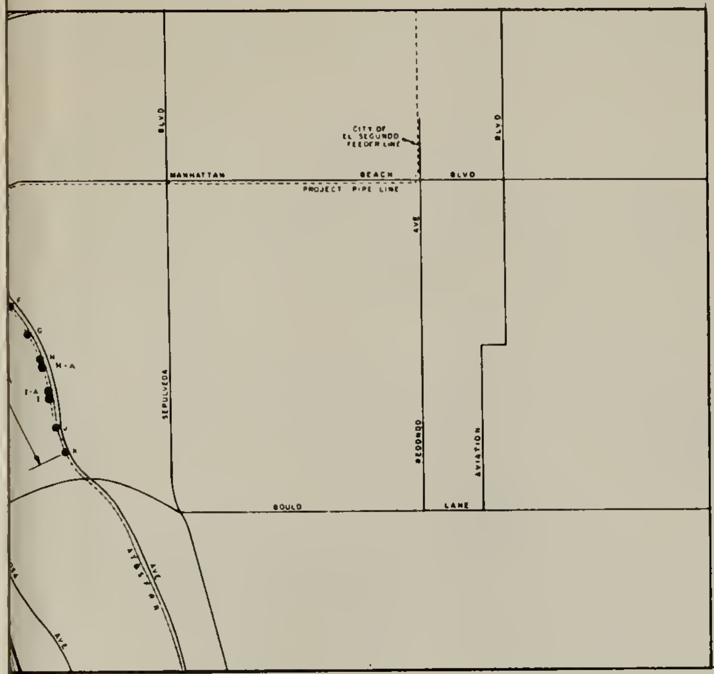

MANHATTAN BEACH
PACIFIC OCEAN
HERMOSA BEACH
ARDMORE
HERMOSA AVE.
A.T. & S.F. R.R.
AVE.
SEPULVEDA BLVD.
REDONDO AVE.
AVIATION BLVD.
MANHATTAN BEACH BLVD.
GOULD LANE
PROJECT PIPE LINE
CITY OF EL SEGUNDO FEEDER LINE
C
D
E
F
G
H
H-A
I-A
I
J
K
LEGEND
—-8— LINES OF EQUAL ELEVATION OF GROUND WATER JANUARY 1953
—-8— LINES OF EQUAL ELEVATION OF GROUND WATER JUNE 1954
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA
WEST COAST BASIN EXPERIMENTAL PROJECT
LINES OF EQUAL ELEVATION OF GROUND WATER
JANUARY 1953 AND JUNE 1954
SCALE OF MILES



LOCATION MAP

ATES IN CUBIC FEET PER SECOND							
WELLS							
E	F	G	H	I-A	J	K	TOTAL
0	0	0	0	0[a]	0	0	0
0	0	0.75	0	0[a]	0	0	0.75
1.05	0	0.54	0	0.36[a]	0	0.48	2.43
1.04	0.63	1.05	0	0.37[a]	0.51	0.74	4.84
0.39	0.37	0.39	0.47	1.03	0.78	0.74	4.41
0.45	0.59	0.64	0.70	1.13	0.55	0.30	4.77
0.53	0.45	0.91	0	1.00	0.26	0.45	3.95
0.58	0	0.74	0.60[b]	0.88	0.43	0.46	4.26

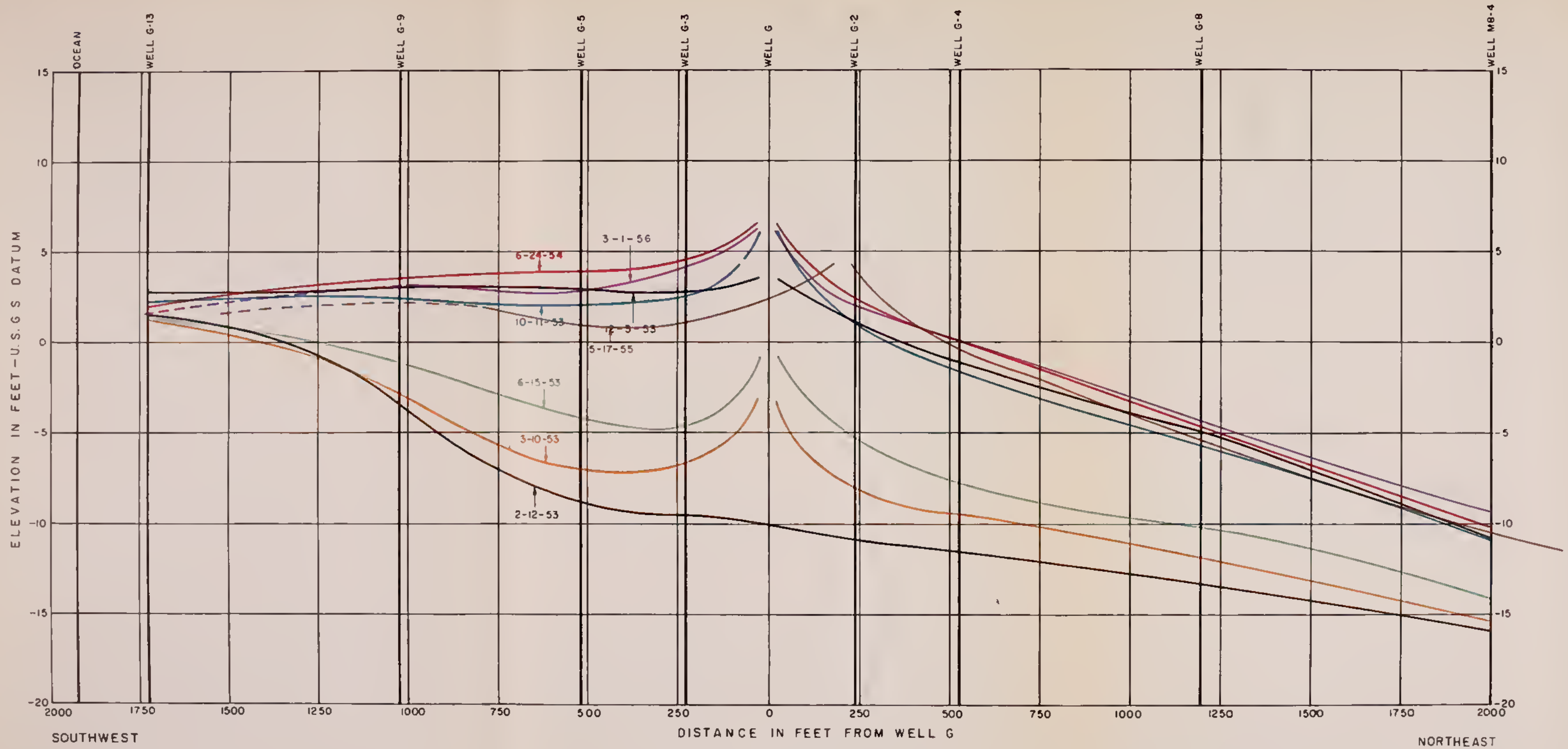
86952-C



LOCATION MAP

ATES IN CUBIC FEET PER SECOND							
WELLS							
E	F	G	H	I-A	J	K	TOTAL
0	0	0	0	0[a]	0	0	0
0	0	0.75	0	0[a]	0	0	0.75
1.05	0	0.54	0	0.36[a]	0	0.48	2.43
1.04	0.63	1.05	0	0.37[a]	0.51	0.74	4.84
0.39	0.37	0.39	0.47	1.03	0.78	0.74	4.41
0.45	0.59	0.64	0.70	1.13	0.55	0.30	4.77
0.53	0.45	0.91	0	1.00	0.26	0.45	3.95
0.58	0	0.74	0.60[b]	0.88	0.43	0.46	4.26

86952-C



LOCATION MAP

DATE	WELLS									
	C	D	E	F	G	H	I-A	J	K	TOTAL
2-12-53	0	0	0	0	0	0	0[a]	0	0	0
3-10-53	0	0	0	0	0.75	0	0[a]	0	0	0.75
6-15-53	0	0	1.05	0	0.54	0	0.36[a]	0	0.48	2.43
10-11-53	0	0.50	1.04	0.63	1.05	0	0.37[a]	0.51	0.74	4.84
12-3-53	0	0.24	0.39	0.37	0.39	0.47	1.03	0.78	0.74	4.41
6-24-54	0	0.41	0.45	0.59	0.64	0.70	1.13	0.55	0.30	4.77
5-17-55	0	0.35	0.53	0.45	0.91	0	1.00	0.26	0.45	3.95
3-1-56	0.29	0.28	0.58	0	0.74	0.60[b]	0.88	0.43	0.46	4.26

INJECTION RATES IN CUBIC FEET PER SECOND

a WELL I
b WELL H-A

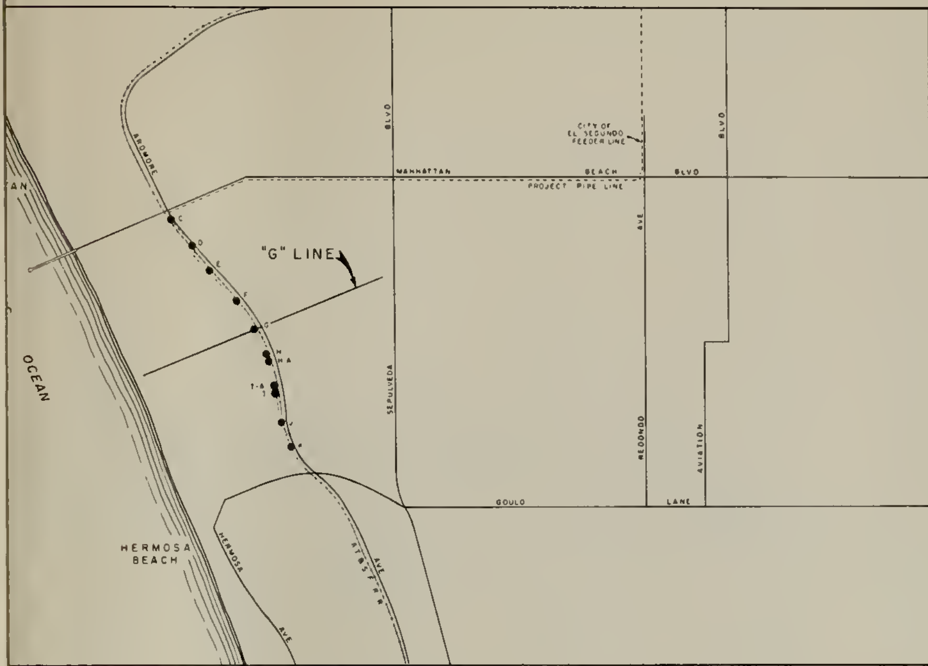
WEST COAST BASIN EXPERIMENTAL PROJECT
PIEZOMETRIC PROFILES ALONG THE "G" LINE

DEPARTMENT OF WATER RESOURCES 1957

LOCATION MAP

INJECTION RATES IN CUBIC FEET PER SECOND										
E	WELLS									
	C	D	E	F	G	H	I-A	J	K	TOTAL
-53	0	0	0	0	0	0	0[a]	0	0	0
-53	0	0	0	0	0.75	0	0[a]	0	0	0.75
-53	0	0	1.05	0	0.54	0	0.36[a]	0	0.48	2.43
53	0	0.50	1.04	0.63	1.05	0	0.37[a]	0.51	0.74	4.84
53	0	0.24	0.39	0.37	0.39	0.47	1.03	0.78	0.74	4.41
-54	0	0.41	0.45	0.59	0.64	0.70	1.13	0.55	0.30	4.77
-55	0	0.35	0.53	0.45	0.91	0	1.00	0.26	0.45	3.95
56	0.29	0.28	0.58	0	0.74	0.60[b]	0.88	0.43	0.46	4.26

I
H-A

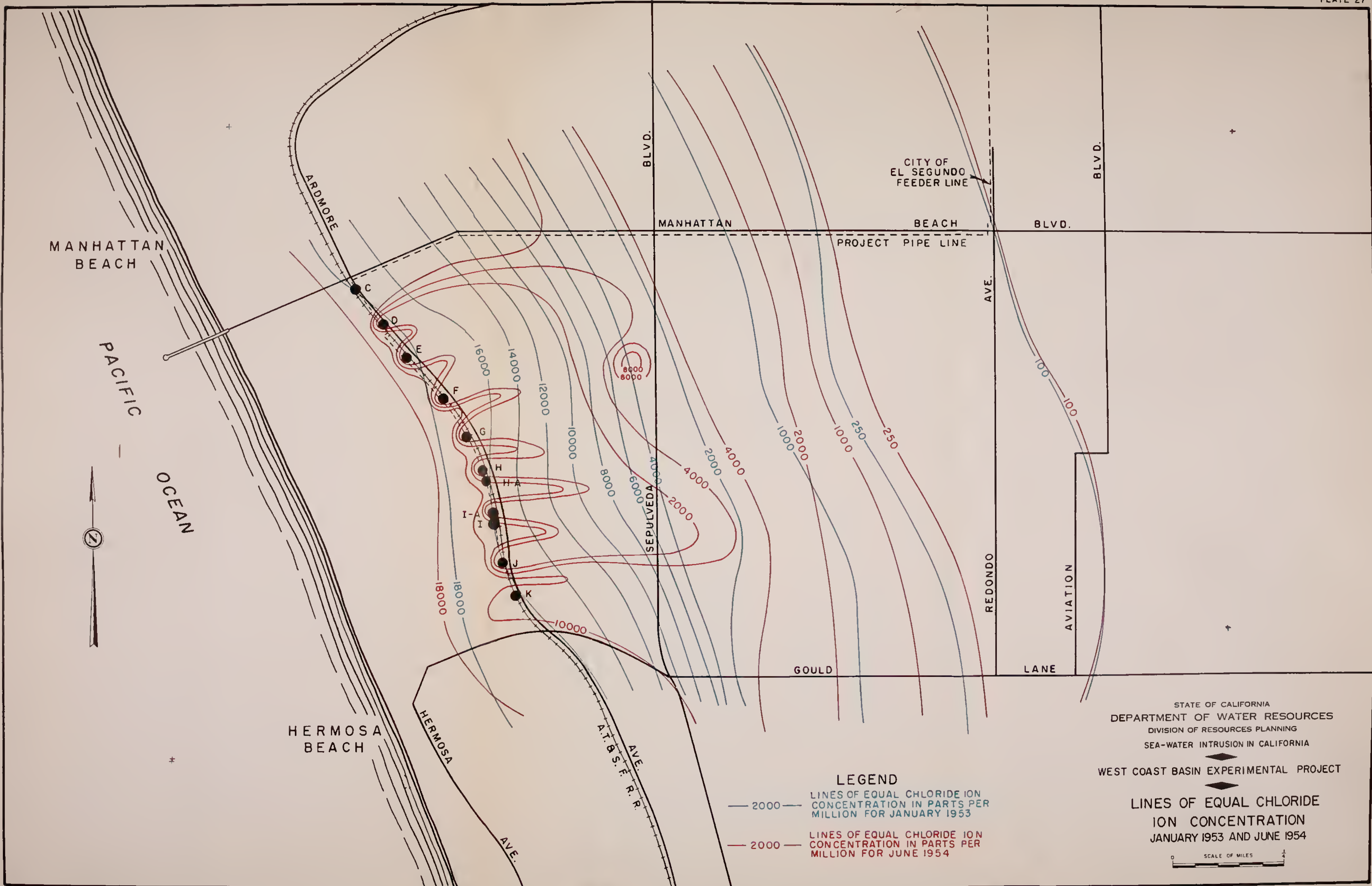


LOCATION MAP

INJECTION RATES IN CUBIC FEET PER SECOND										
E	WELLS									
	C	D	E	F	G	H	I-A	J	K	TOTAL
-53	0	0	0	0	0	0	0[a]	0	0	0
-53	0	0	0	0	0.75	0	0[a]	0	0	0.75
-53	0	0	1.05	0	0.54	0	0.36[a]	0	0.48	2.43
53	0	0.50	1.04	0.63	1.05	0	0.37[a]	0.51	0.74	4.84
53	0	0.24	0.39	0.37	0.39	0.47	1.03	0.78	0.74	4.41
-54	0	0.41	0.45	0.59	0.64	0.70	1.13	0.55	0.30	4.77
55	0	0.35	0.53	0.45	0.91	0	1.00	0.26	0.45	3.95
56	0.29	0.28	0.58	0	0.74	0.60[b]	0.88	0.43	0.46	4.26

I
H-A

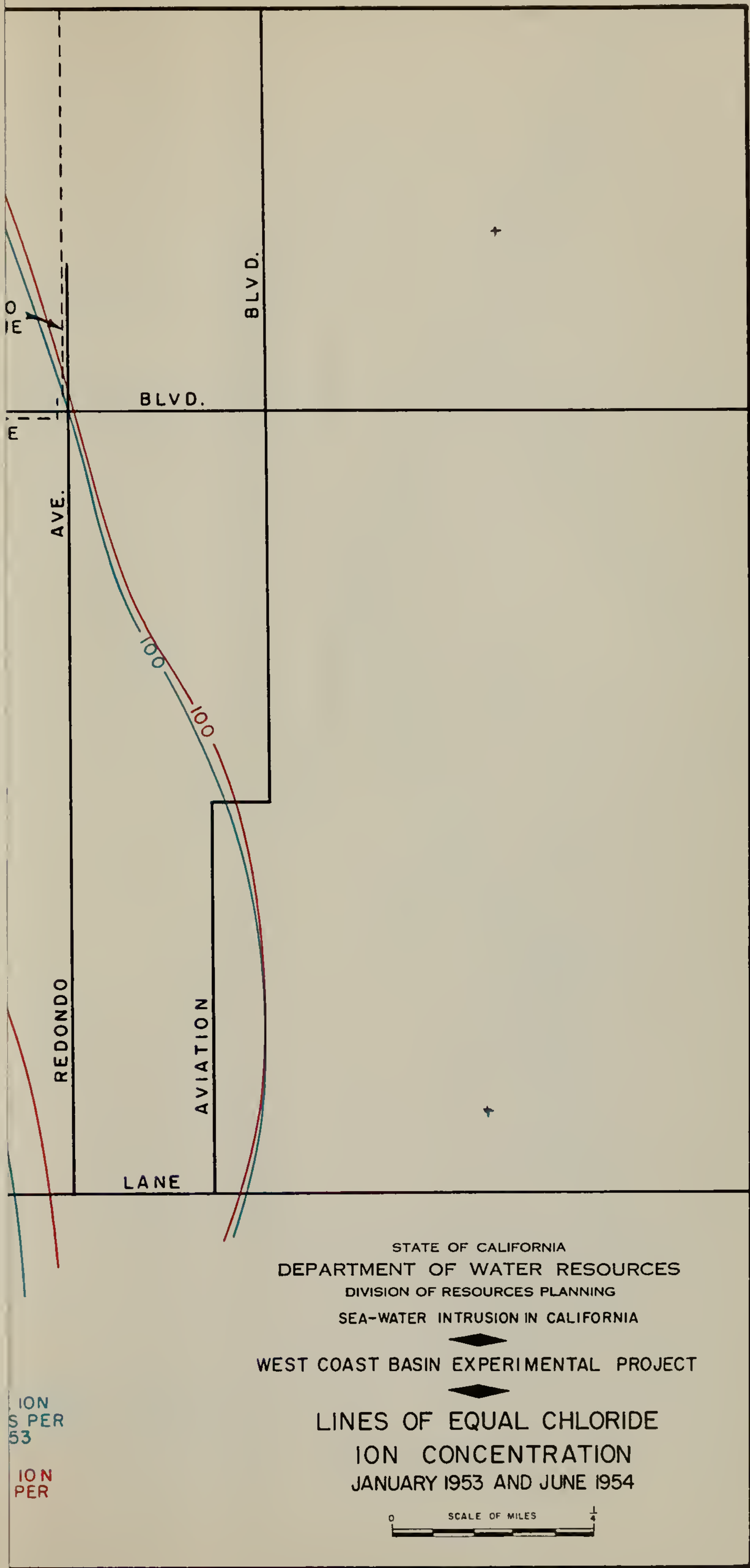
86952-C



STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

WEST COAST BASIN EXPERIMENTAL PROJECT

LINES OF EQUAL CHLORIDE ION CONCENTRATION
JANUARY 1953 AND JUNE 1954

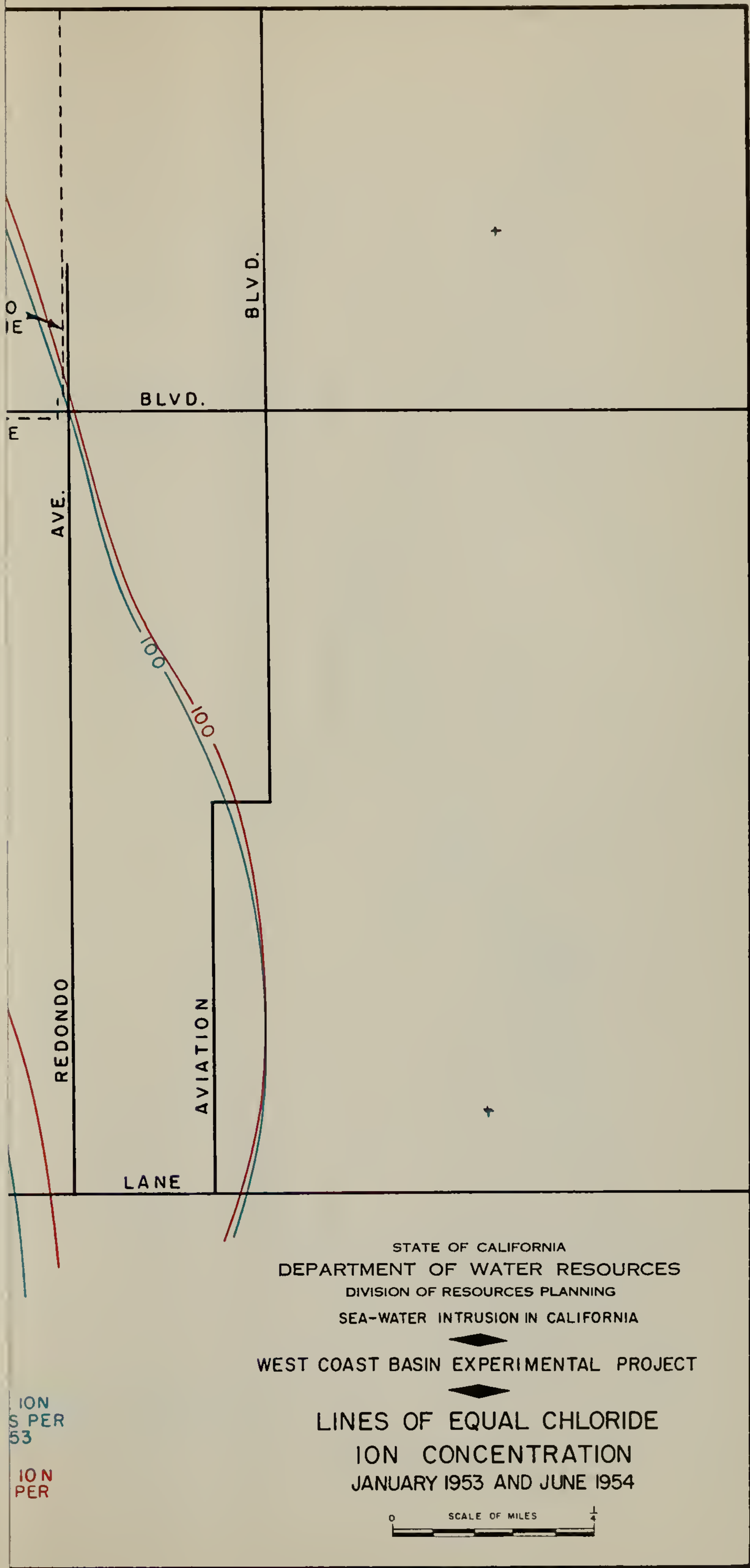


STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING
SEA-WATER INTRUSION IN CALIFORNIA

WEST COAST BASIN EXPERIMENTAL PROJECT

LINES OF EQUAL CHLORIDE ION CONCENTRATION
JANUARY 1953 AND JUNE 1954

SCALE OF MILES
0 — 1/4



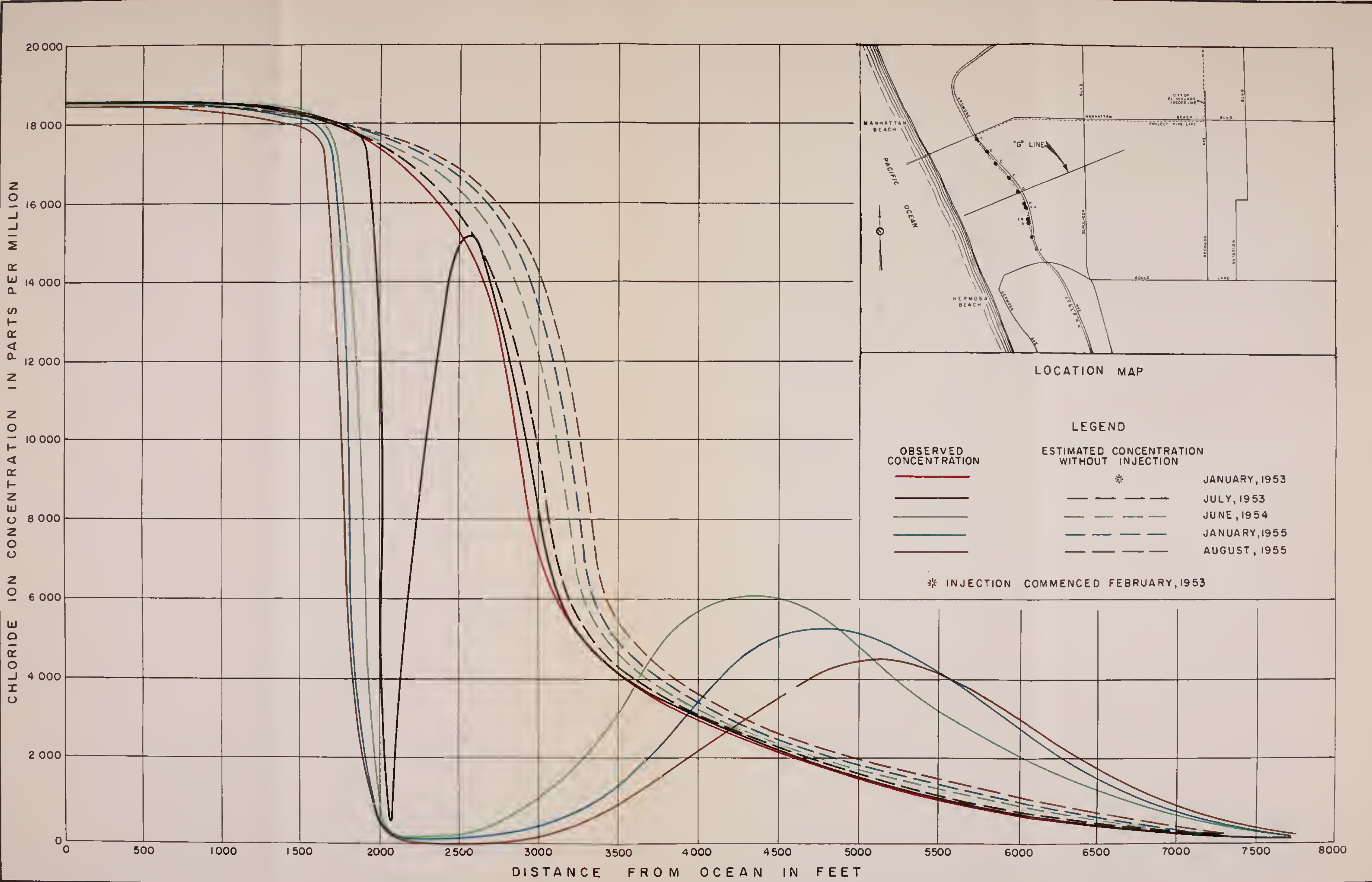
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

WEST COAST BASIN EXPERIMENTAL PROJECT

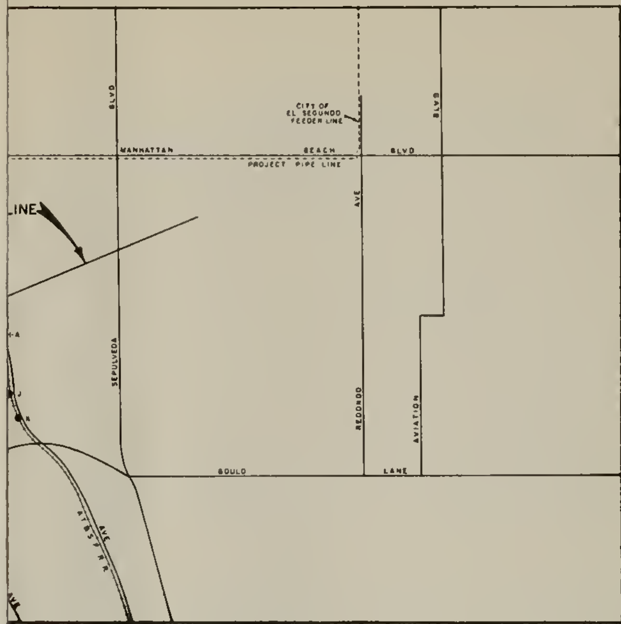
LINES OF EQUAL CHLORIDE ION CONCENTRATION
JANUARY 1953 AND JUNE 1954

SCALE OF MILES



WEST COAST BASIN EXPERIMENTAL PROJECT

CHLORIDE ION CONCENTRATION ALONG THE "G" LINE BEFORE AND AFTER INJECTION



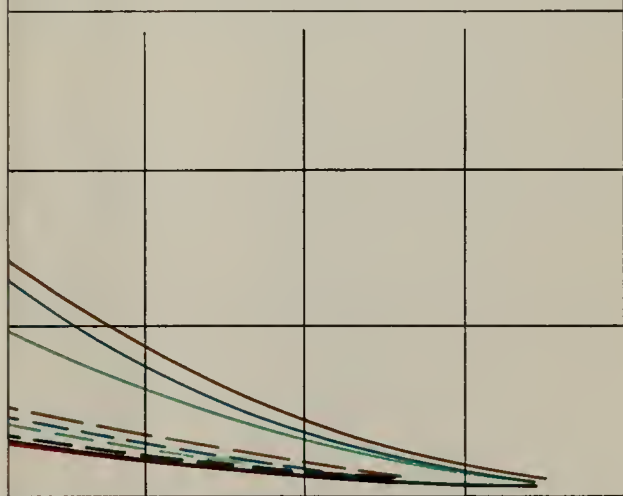
LOCATION MAP

LEGEND

ESTIMATED CONCENTRATION
WITHOUT INJECTION

✻	JANUARY, 1953
— — — —	JULY, 1953
— — — —	JUNE, 1954
— — — —	JANUARY, 1955
— — — —	AUGUST, 1955

OMMENCED FEBRUARY, 1953



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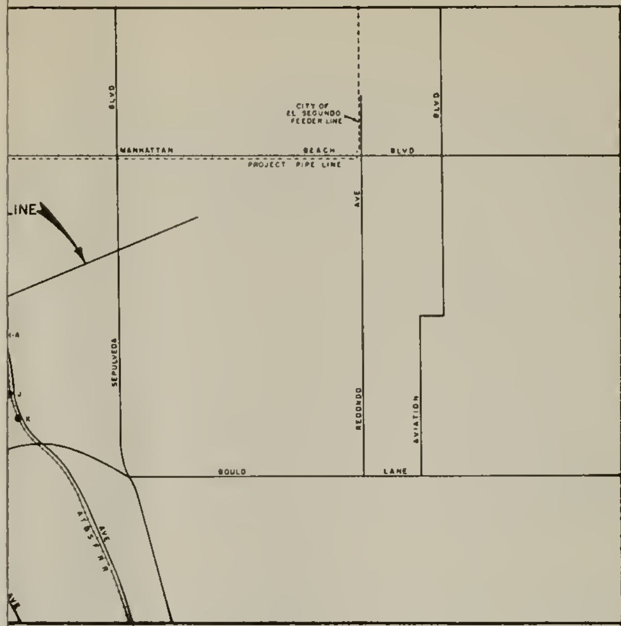


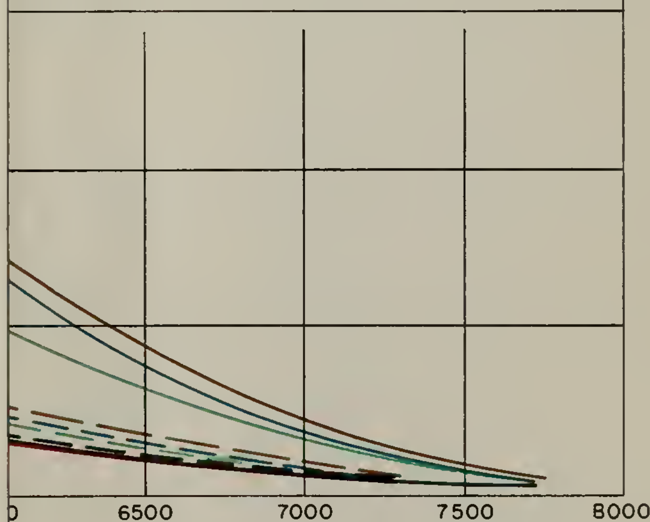
LOCATION MAP

LEGEND

ESTIMATED CONCENTRATION WITHOUT INJECTION

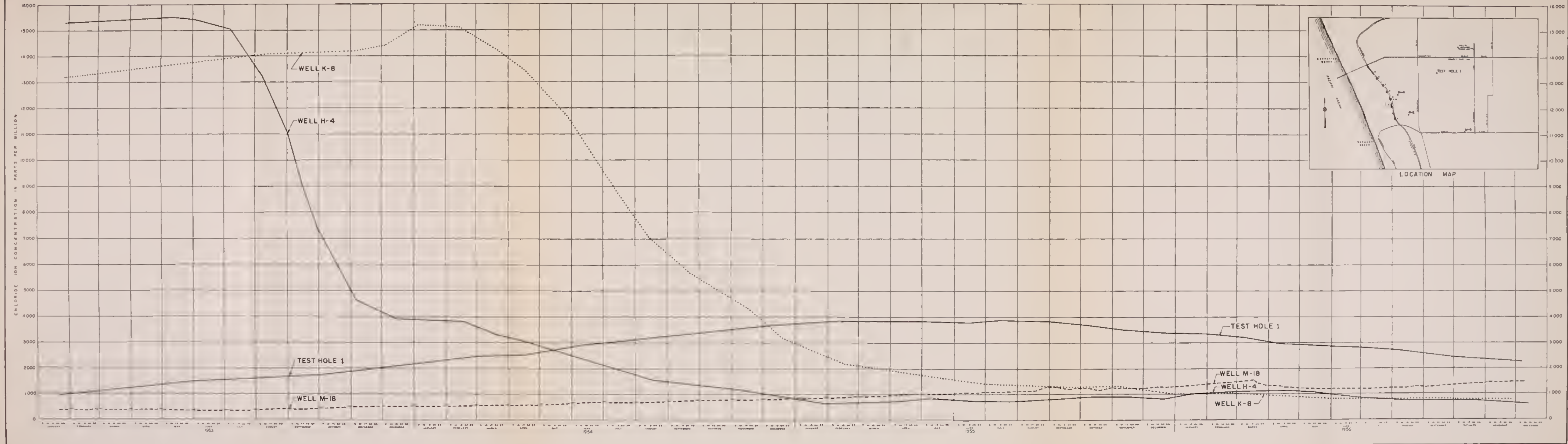
✻	JANUARY, 1953
— — — —	JULY, 1953
— — — —	JUNE, 1954
— — — —	JANUARY, 1955
— — — —	AUGUST, 1955

OMMENCED FEBRUARY, 1953



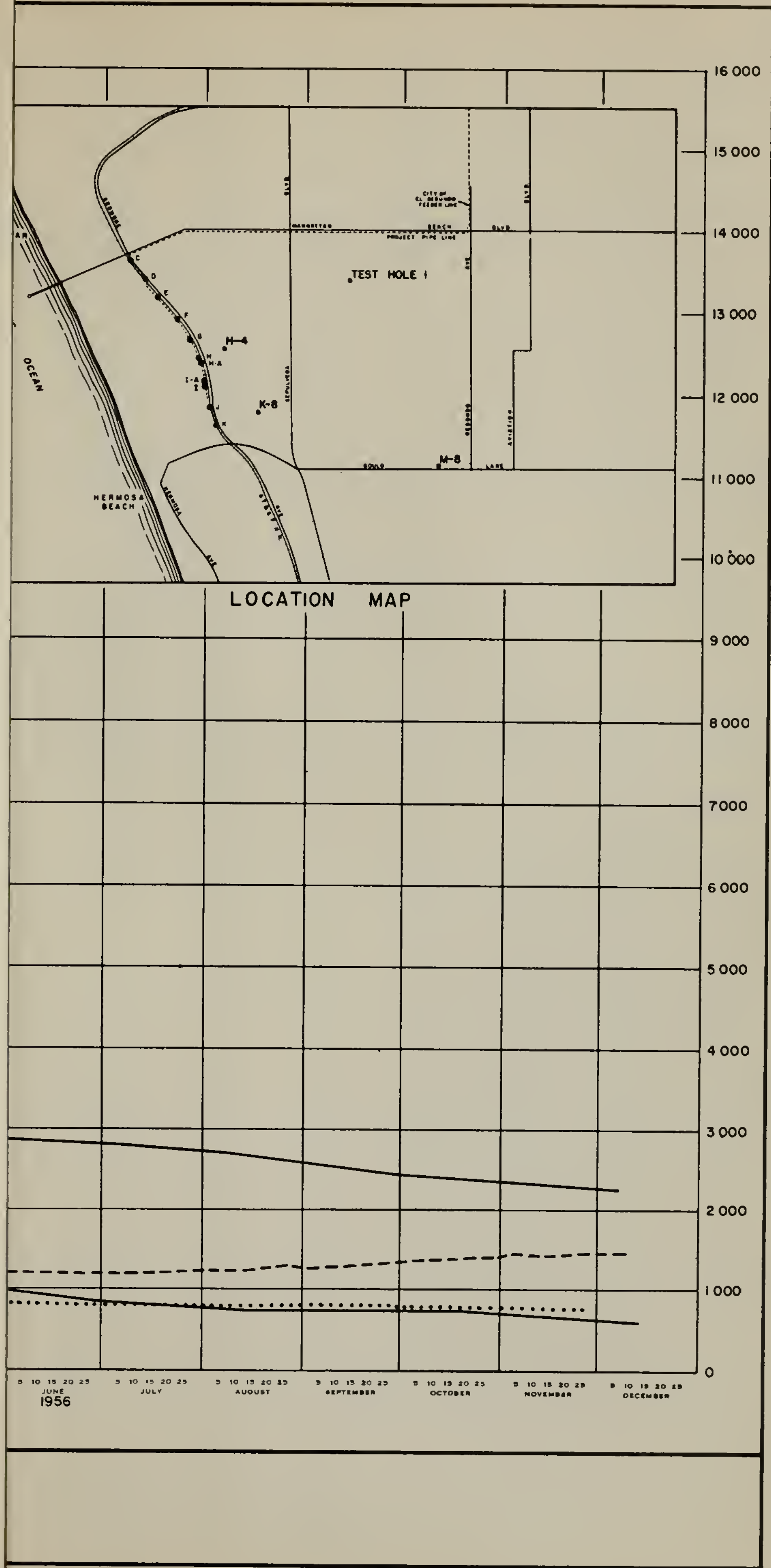
N

86952-C

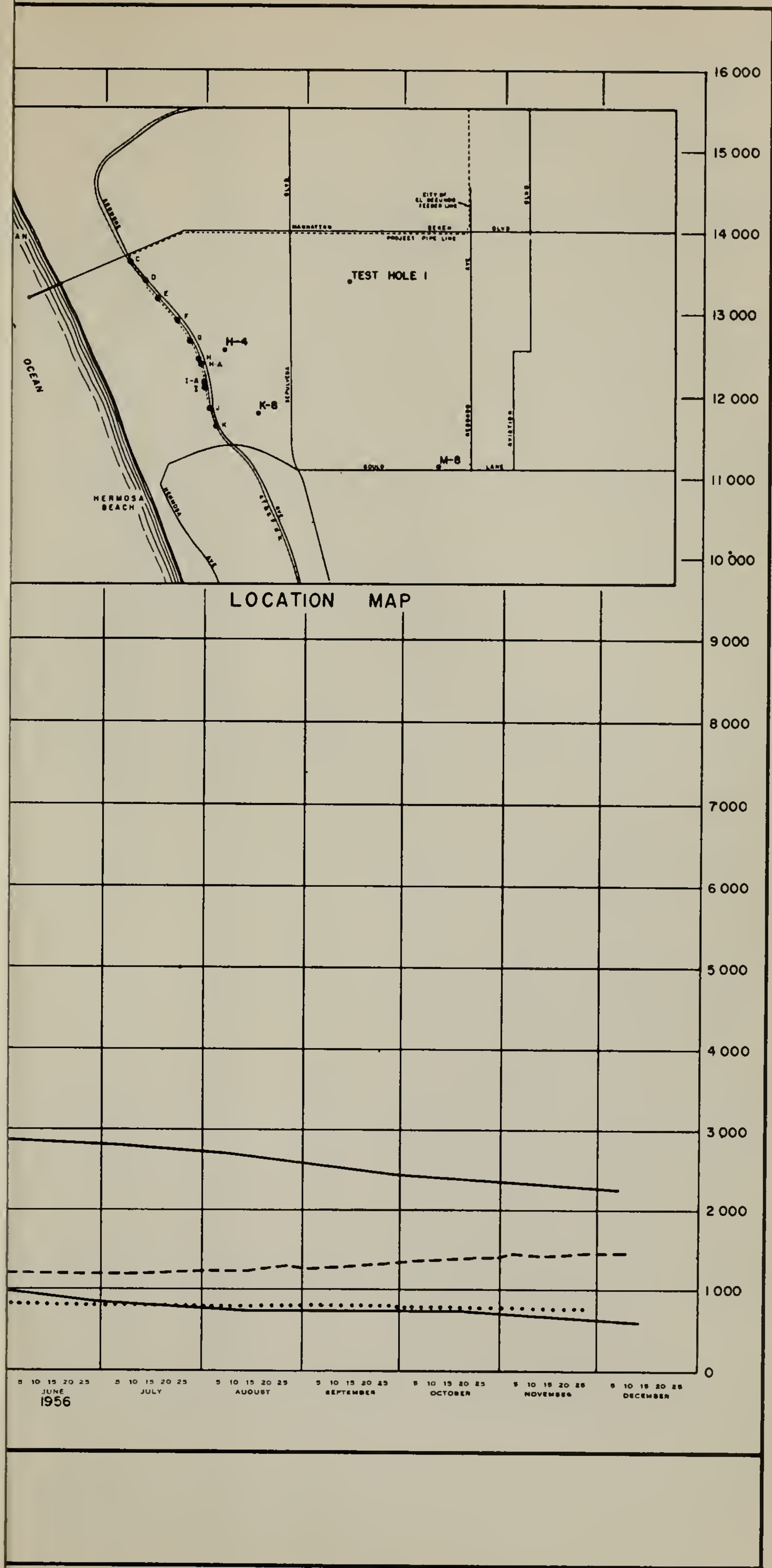


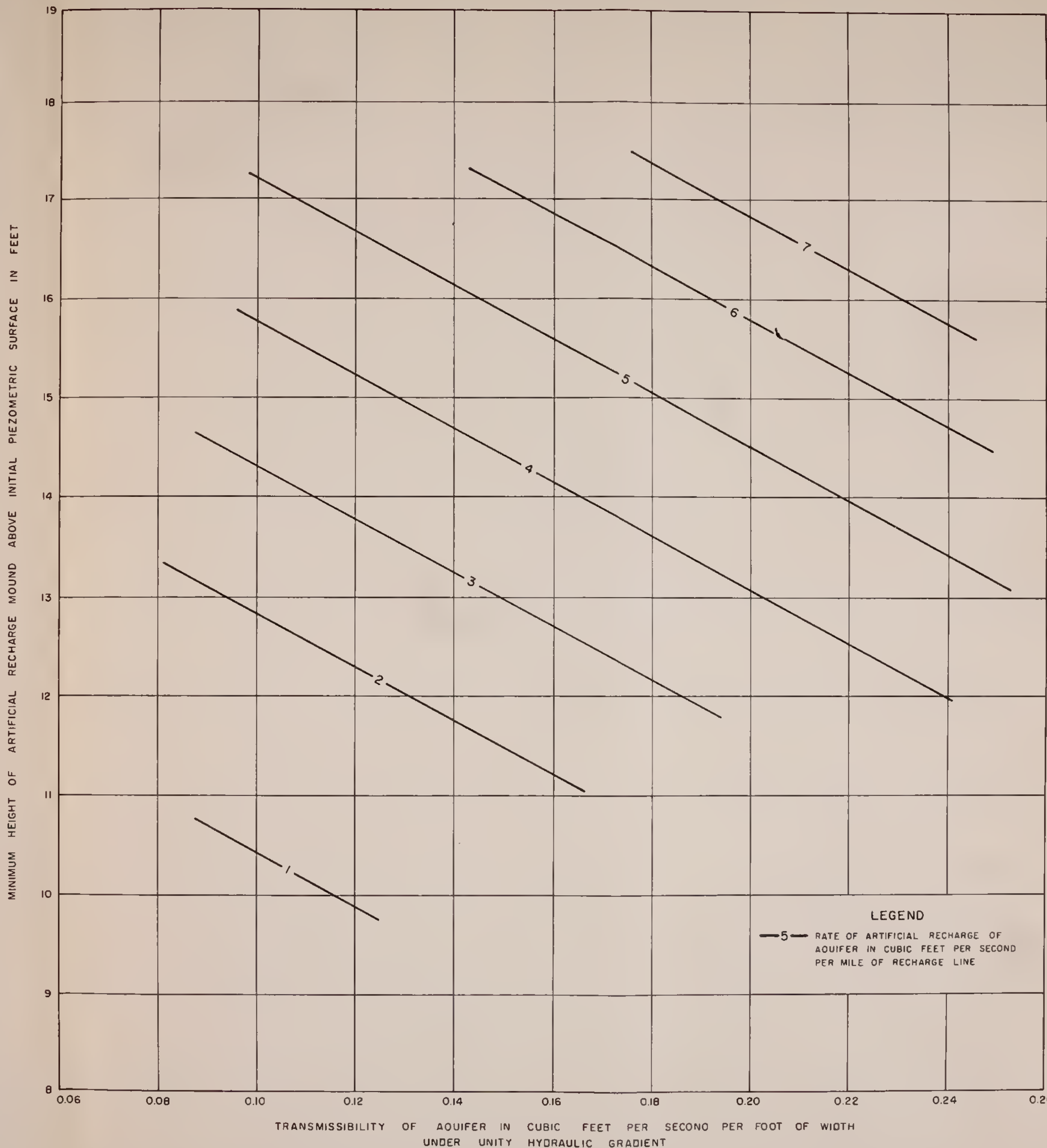
WEST COAST BASIN EXPERIMENTAL PROJECT
CHLORIDE ION CONCENTRATION AT SELECTED WELLS

DEPARTMENT OF WATER RESOURCES 1957

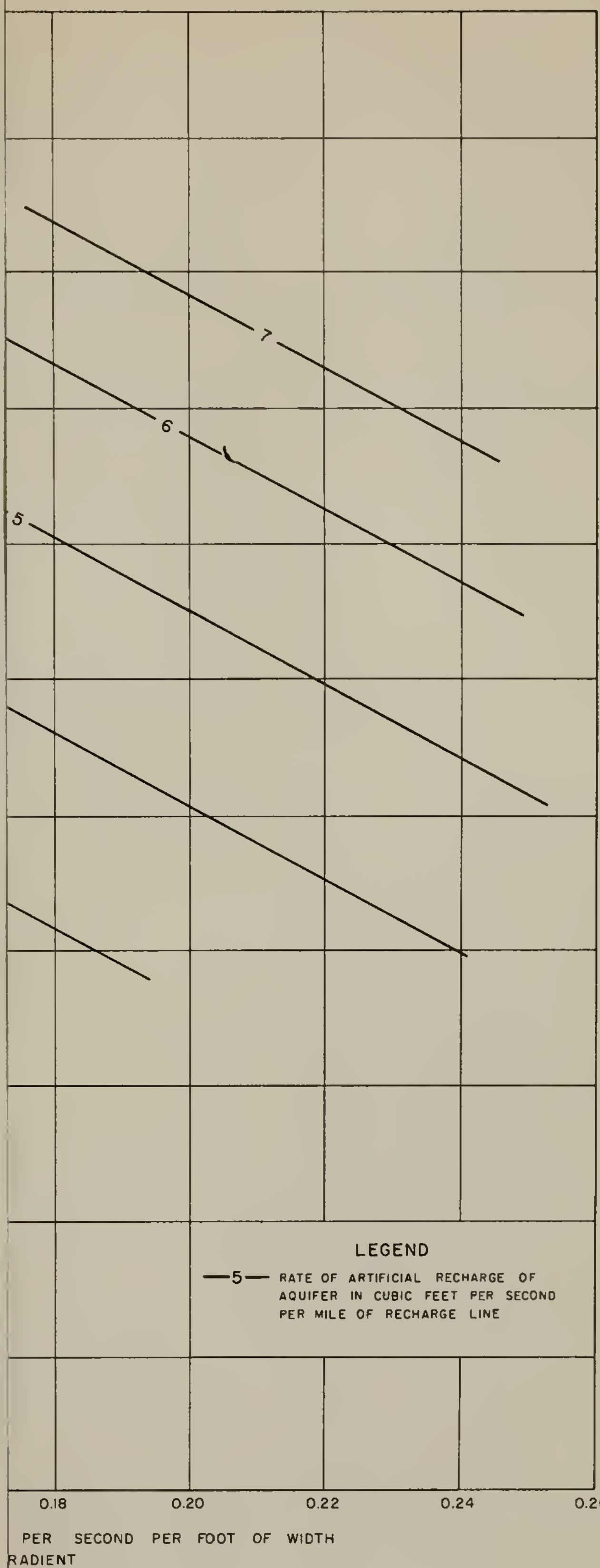


LOCATION MAP
OCEAN
HERMOSA BEACH
TEST HOLE 1
H-4
K-8
M-8
SEPULVEDA
16 000
15 000
14 000
13 000
12 000
11 000
10 000
9 000
8 000
7000
6 000
5 000
4 000
3 000
2 000
1 000
0
JUNE
1956
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER

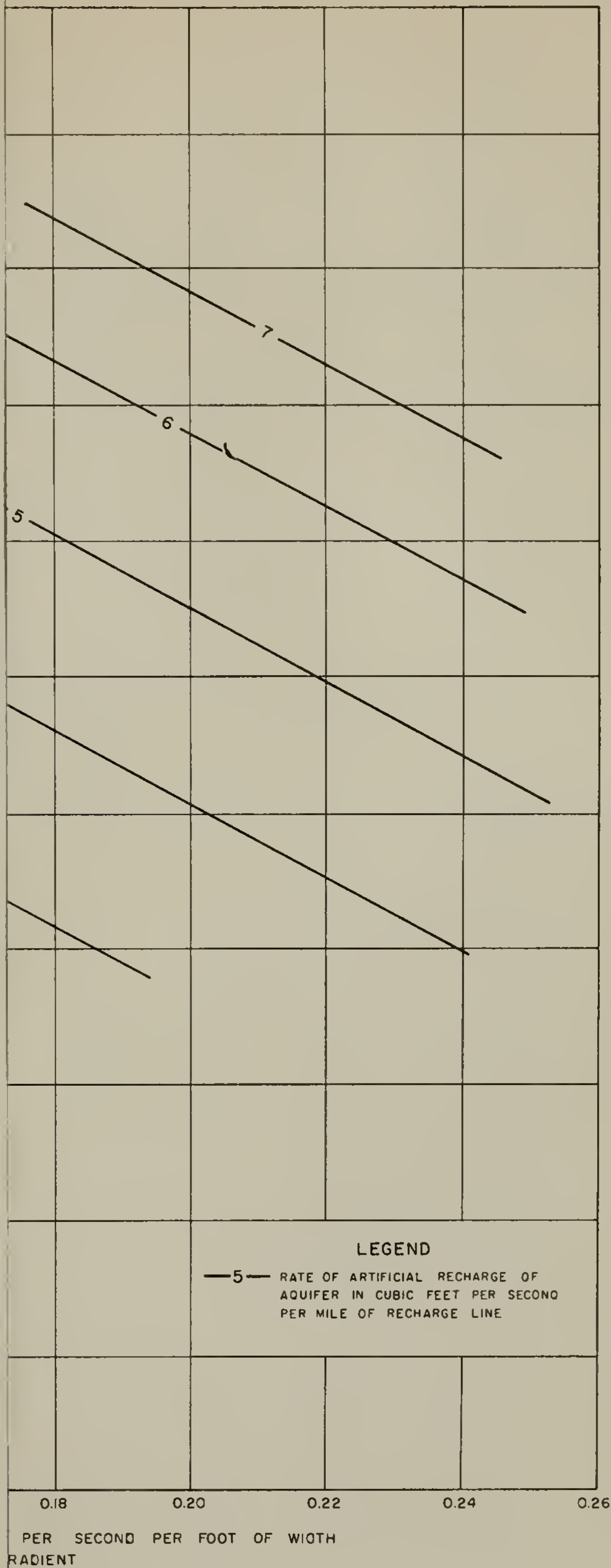

16 000
15 000
14 000
13 000
12 000
11 000
10 000
9 000
8 000
7000
6 000
5 000
4 000
3 000
2 000
1 000
0
LOCATION MAP
TEST HOLE I
H-4
K-8
M-8
OCEAN
HERMOSA BEACH
SEPULVEDA
5 10 15 20 25
JUNE
1956
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER



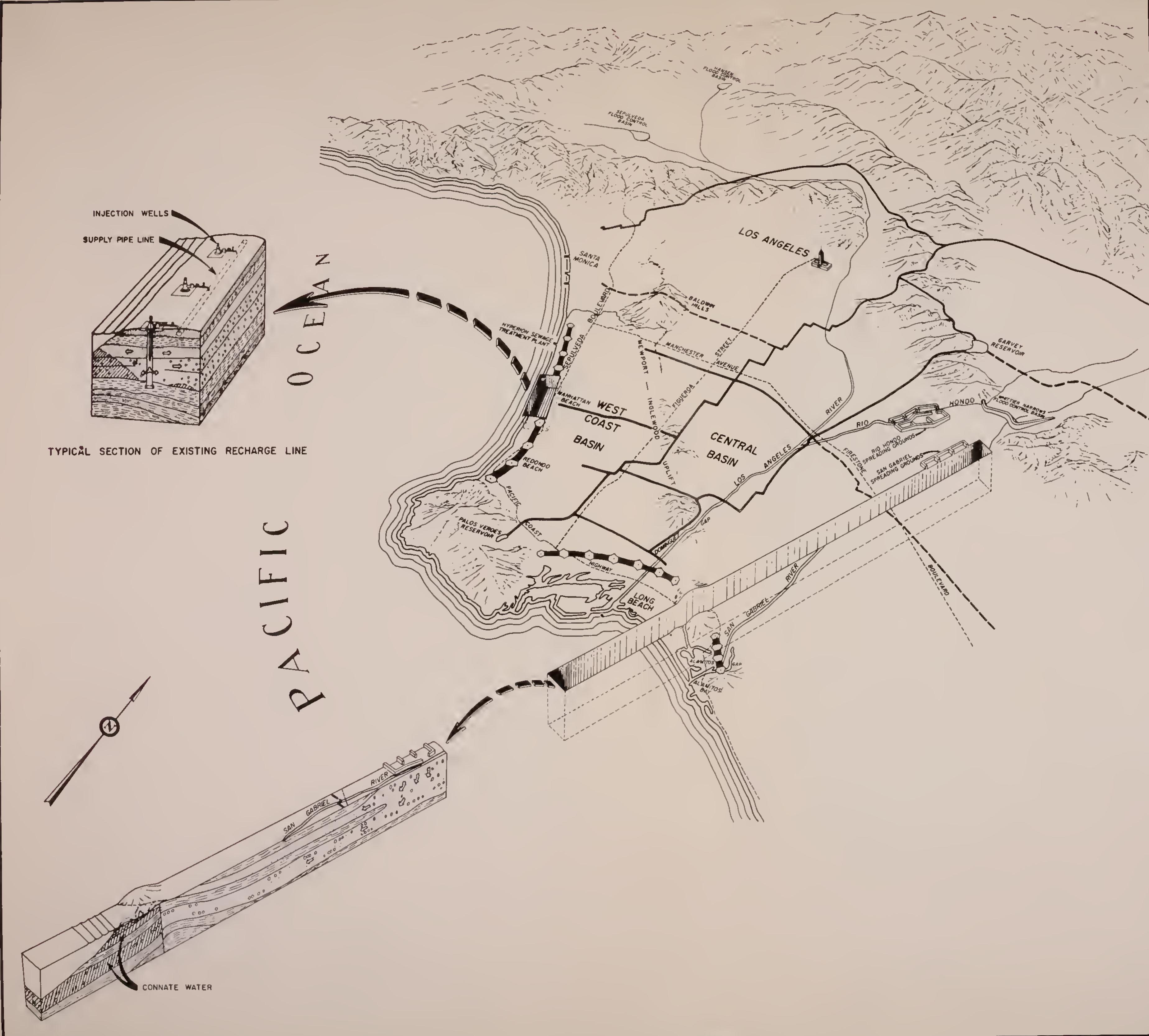
RELATIONSHIP OF MINIMUM HEIGHT OF ARTIFICIAL RECHARGE MOUND, TRANSMISSIBILITY OF AQUIFER, AND RATE OF RECHARGE



RTIFICIAL RECHARGE MOUND,
RATE OF RECHARGE



RTIFICIAL RECHARGE MOUND,
RATE OF RECHARGE



LEGEND

EXISTING PROJECT AND PLAN UNDER INVESTIGATION FOR INJECTION OF WATER THROUGH WELLS

COLORADO RIVER WATER DISTRIBUTION LINES

SAND

GRAVEL

SILT, CLAY, AND SHALE

DIRECTION OF GROUND WATER MOVEMENT

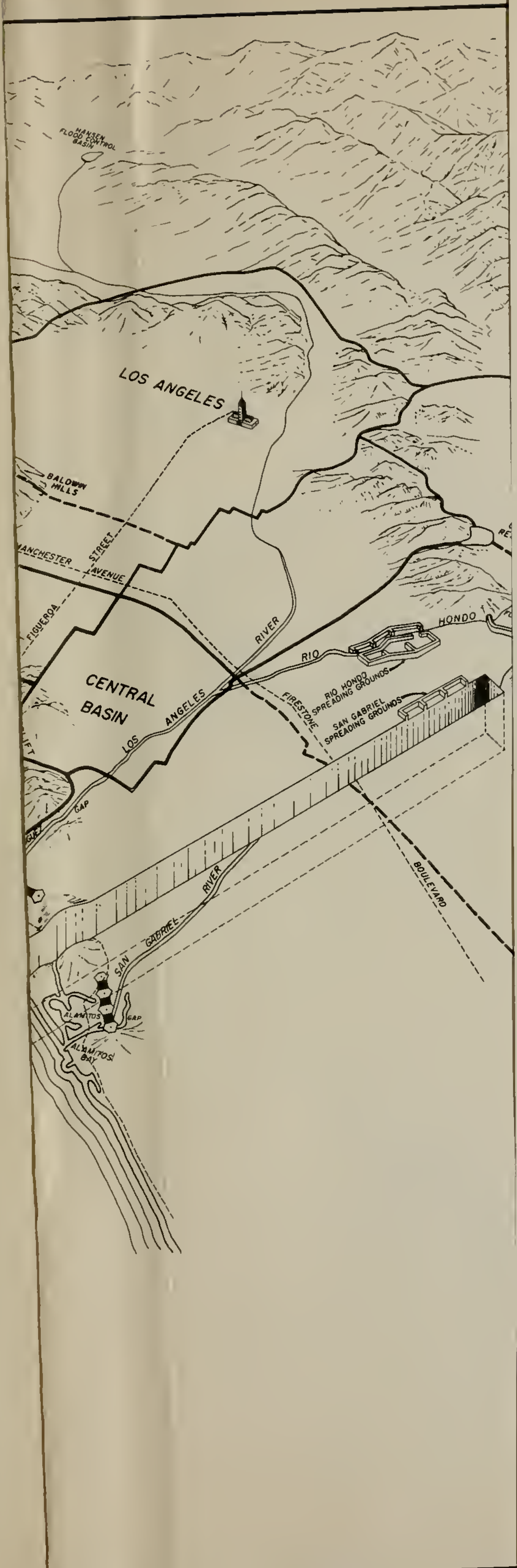
FRESH WATER / SEA WATER — INTERFACE BETWEEN SEA AND FRESH WATER

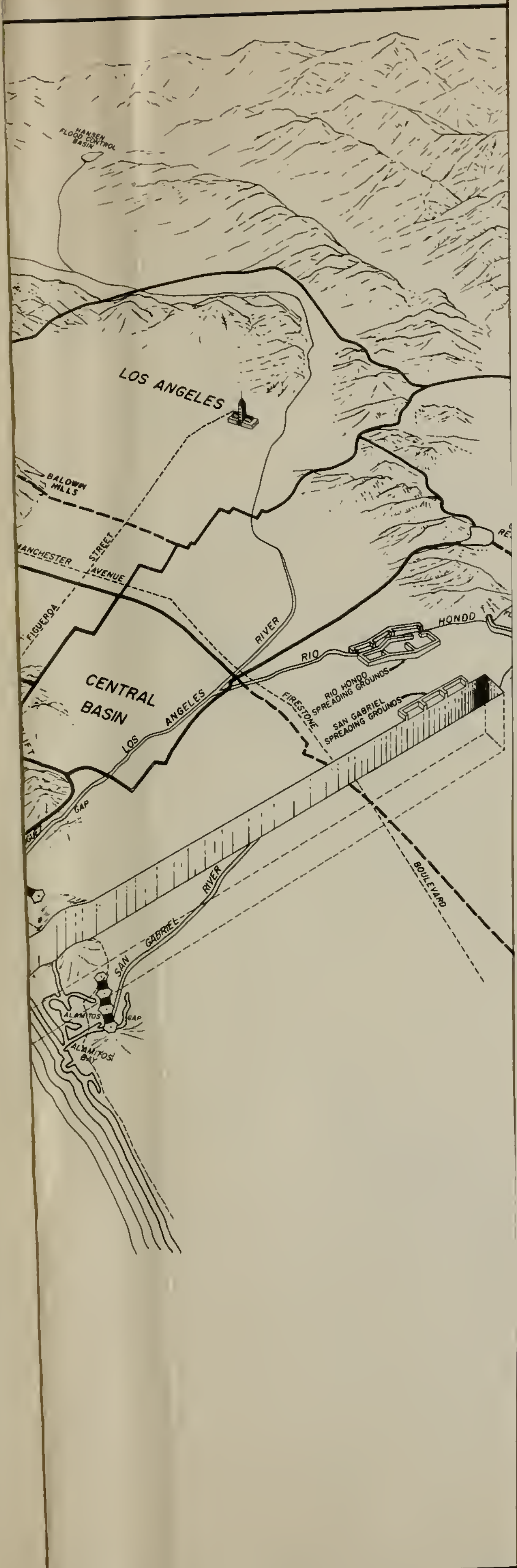
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

SEA-WATER INTRUSION IN CALIFORNIA

WEST COAST BASIN EXPERIMENTAL PROJECT

PLAN UNDER INVESTIGATION FOR CONTROL OF SEA-WATER INTRUSION IN LOS ANGELES COASTAL PLAIN


HANSEN FLOOD CONTROL BASIN
LOS ANGELES
BALDWIN HILLS
MANCHESTER
AVENUE
FIGUEROA
STREET
CENTRAL BASIN
LOS ANGELES RIVER
RIO HONDO
RIO HONDO SPREADING GROUNDS
SAN GABRIEL SPREADING GROUNDS
FIRESTONE
BOULEVARD
SAN GABRIEL RIVER
GAP
ALAMITOS
GAP
ALAMITOS BAY


HANSEN FLOOD CONTROL BASIN
LOS ANGELES
BALDWIN HILLS
MANCHESTER
AVENUE
FIGUEROA
STREET
CENTRAL BASIN
LOS ANGELES RIVER
RIO HONDO
RIO HONDO SPREADING GROUNDS
SAN GABRIEL SPREADING GROUNDS
FIRESTONE
BOULEVARD
SAN GABRIEL RIVER
GAP
ALAMITOS
ALAMITOS BAY